FOUNDATION FIELDBUS PRELIMINARY

TECHNOLOGY TRANSFER PLAN

Prepared for:

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FOUNDATION FIELDBUS
DRAFT TECHNOLOGY TRANSFER PLAN

Introduction

FOUNDATION™ fieldbus is a digital communications and control technology developed in response to the demands of end users in the process control and manufacturing automation industries. The requirements include the need to integrate control, data collection and communication using a solution based on an open standard. The standard needed to be sufficiently comprehensive to assure interoperability of devices from multiple manufacturers, while also supporting the seemingly contradictory requirement of encouraging innovation and advances in device technology itself.

The specification has been in development since August 1984. Testing of the major phase of work was completed and final specifications suitable for implementing products were published in December of 1996. An extended phase of work is currently in progress.

Development and testing of the specification has been conducted by the cooperative efforts of a large number of industrial companies in North and South America, Europe, and Asia. The application requirements addressed include continuous and batch control in the fluid processing industries, and discrete parts manufacturing and high speed sequence control in manufacturing automation. In general, the problems addressed are common across a wide range of applications, though the details of device implementation are typically application specific.

Significant benefits are being realized by suppliers as a result of sharing the cost of an exceedingly comprehensive specification development and maintenance process across many companies. The wide participation has also assured consideration of varying viewpoints from different suppliers and different geographical areas. Benefits to end-users result from the soundness of the resulting specification, the freedom to mix and match products from a variety of manufacturers, and dramatically reduced costs for system integration and commissioning.

This document is written for managers who have little or no prior knowledge of Foundation fieldbus. This plan has grown out of the joint NASA/industry consortia SuperMOCA program, which has been investigating the use of this technology during the past two years and therefore does not include an in-depth technical evaluation. The purpose is to describe how FOUNDATION fieldbus technology can be transferred to a new area of application, aerospace, and to show that similar benefits would accrue. To describe how the benefits are derived, as well as to illustrate the generality of the technology, it is necessary to first review the infrastructure provided by the Fieldbus Foundation, and to then give example illustrations of the technology itself.

PART I - SYNOPSIS OF FIELDBUS FOUNDATION

Purpose

In 1992, four industrial controls suppliers announced their intention to implement an open communication and control specification based on a sub-set of an emerging international standard. In doing so they would collectively put in place a whole range of technology including communications and applications software, chip designs, development and test tools, and other related software. They recognized the need for a neutral organization which could provide an independent repository for commonly developed intellectual property, and to assure that no single company could control the technology. This organization was initially called the *ISP Foundation*. Three years after its creation, the Foundation merged with another entity and the name was changed to the *Fieldbus Foundation*. From the beginning, other automatic control suppliers and users were actively recruited worldwide to help fund the activity, to contribute technology and to build a broadly accepted communication and control solution.

The Foundation also provides an infrastructure for maintenance, dissemination and promotion of the attendant technology, and the structure within which extensions and new developments can take place and remain coordinated with the existing technology. This includes laboratory and field tests required to assure that written specifications are implementable and perform as intended.

Organization

As a legal entity, the Foundation is a not-for-profit corporation organized under the National Cooperative Research Act of 1984. Its ongoing operations are funded through membership dues, the sale of software and specifications, and consulting and training services. The non-recurring costs associated with special projects have been funded by pledges from certain participating members.

The work of the Foundation is accomplished by a mixture of a core group of permanent employees, a large number of part-time participants volunteered by member companies, and occasionally sub-contracted outside experts.

Each group serves somewhat different needs and the contribution of all participants is essential. Like any corporation, the Foundation has a board of directors elected by the shareholders, in this case the membership. There are presently 11 board seats. Directors are elected for two year terms with approximately half of the terms expiring each year. These are volunteer positions and board member companies currently represent America, Asia and Europe in roughly equal numbers.

The President and CEO of the Foundation is a full-time paid position and reports to the board of directors. The Foundation's permanent staff and various volunteer committees report to the president as shown in Figure 1.

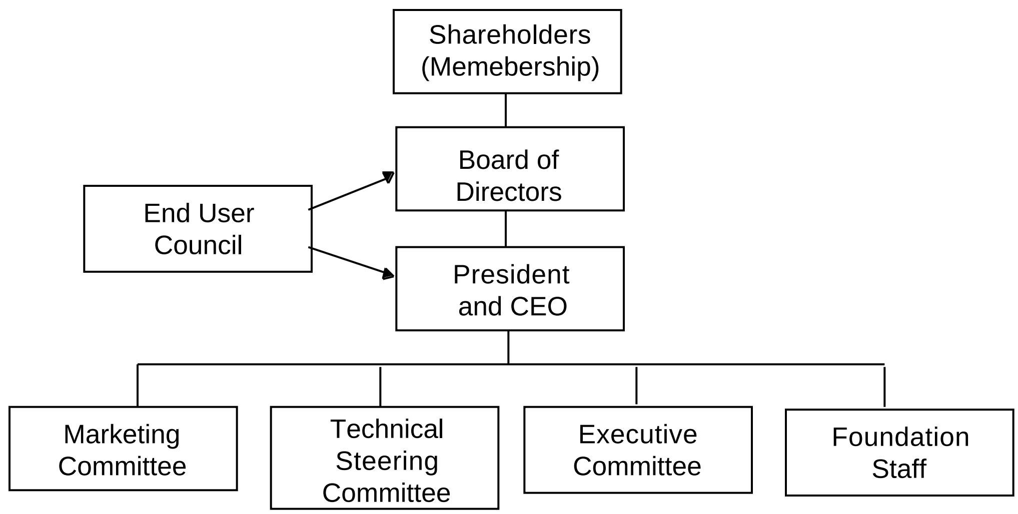


Figure 1. Organization of the Fieldbus Foundation.

Other than the president and the Foundation staff, all other groups shown in Figure 1 are staffed with volunteers provided by member companies. Not shown are a number of teams and working groups, some temporary, some permanent, reporting into this organization. The functions, organization and scale of the most important of these groups will be discussed in the next section.

Working Groups and Teams

While many of the activities of the Foundation are performed by volunteer personnel, it should not be assumed that these are incidental or insignificant efforts. To finalize the present communication specification, the H1 Fieldbus Specification Development Team was formed in August, 1994, and consisted of 25 full-time engineers from 16 companies and from three world areas. The team met as a group in dedicated facilities for two weeks out each month between August 1994 and June 1995, with the members continuing to work in their home offices for the intervening weeks. This effort was only to conclude the work of an earlier team of similar size and intensity, which had been underway since early 1992.

A similar commitment, in terms of person-hours, has been made by several teams which developed the specifications for the function block application. This specification, which now consists of five parts, is of equal importance and complexity as the communication specification. Other examples of intensive volunteer effort will be cited later in the section on current Foundation Programs.

Of the volunteer groups shown in Figure 1, the eight person Technical Steering Committee (TSC) typically meets from six to eight times per year, for a period of typically three days. The Marketing and Executive committees meet for two to three days, slightly less often. The Board of Directors will generally meet three to four times per year for one day meetings, and conducts teleconferences at about that same frequency.

The board reviews all activities of the Foundation and actively sets the direction for marketing and technical programs. The board also monitors the financial condition of the foundation and helps in securing the necessary resources, human and financial, necessary for the achievement of the Foundation’s goals.

The Marketing Committee works with an outside public relations firm for development of advertising and planning of trade shows. It also advises on packaging and pricing issues for various Foundation products. The Executive Committee provides council to the president and carries out a variety of special projects.

There are several End User Advisory Counsels which are organized regionally. These typically meet one or two times a year for one day meetings. The president of the Foundation coordinates these events and uses feedback from the groups on various issues, policies and questions.

The Foundation engages in the development of new specifications, extensions to existing specifications, new software, tools or other items. New development programs require the approval of the president or board, depending on the scale of the initiative. Approved programs are carried out by technical teams operating under the direction of the Technical Steering Committee (TSC). An example will be described in a later section.

The TSC is also responsible for supervision of the maintenance of specifications, software, test programs and other technical activities. Most of this work is carried out by other volunteer working groups or teams.

Composition of, and membership on, the various technical teams is approved by the TSC. In all cases a Foundation staff member is involved to provide administrative support and sometimes technical expertise. Other members are mostly volunteered by member companies. In some cases, where necessary, outside experts are brought in under contract. Companies who provide volunteers benefit substantially by being able to influence the programs, by being “plugged in” and getting advanced understanding of specifications or software, and by being well networked with the experts in various areas.

Programs

Since its incorporation, the Foundation has conducted a number of major programs such as the specification projects mentioned earlier. As these project are completed, there is normally the need for another program to provide maintenance or utilization of the result of the first. This section will describe the major programs which are currently underway in the Foundation.

Because the specifications are open, implementations have been developed by numerous suppliers and more are expected. To assure a high level of compliance with the specifications, and hence a level of quality of products in the marketplace, the Foundation maintains a testing program. Two test systems were created in earlier development programs. Today, there are ongoing programs to test the conformance of communication stacks and the interoperability of complete devices.

The earlier specification development work provided a complete and thorough solution for process automation. Applications in manufacturing automation were not adequately satisfied. In particular, higher speed communications and some additional functionality is required. A very significant specification development programs is currently underway to serve this need.

One of the strengths of the FOUNDATION fieldbus technology is that it contains a mechanism for handling manufacturer specific parameters without custom programming. The technology, called Device Descriptions, or DD, requires a set of DD files and certain software to be made available to host systems. The Foundation has an on-going program providing critical support for this capability.

Conformance testing

The Foundation maintains a test program to assure the conformance of communication stacks which claim to be FOUNDATION fieldbus compliant. A Conformance Test System (CTS) was developed earlier under another program to deal with this issue. The system includes an automatic test machine running on a PC, and several hundred test cases. The test system was developed under contract by the Fraunhofer Institute in Karlsruhe, Germany. A schematic of the conformance test system is given in Appendix I.

The Foundation has established a set of rules which define how, when, and how often a communication stack must be tested in order to become and remain *registered* by the Foundation. The Foundation avoids the term certification and makes no guarantees with regard to registered stacks, other than that a registered stack has passed the prescribed test schedule.

Not all characteristics of a stack can be tested by the automatic system, there is also a prescribed set of manual tests that are required. The Foundation provides a Conformance Test Kit (CTK) which contains all the necessary software, test cases and procedures needed to conduct the conformance test of a communication stack. This is useful to stack developers during the development period. The Foundation does not, however, accept the results of self-testing as a basis for stack registration.

Stack registration requires that the tests be performed at an accredited third party test agency. The agency provides a test report which is submitted to the Foundation as the basis for registration. At this time, the only accredited test agency in the world is the Fraunhofer Institute in Karlsruhe.

Interoperability testing

The Foundation maintains a second test program to assure that complete devices conform not only to the communication protocol, but to the specification for the function block application which also runs in the devices. This program is part of the effort to assure that products that claim to be FOUNDATION fieldbus compliant are actually interoperable with products from other manufacturers making the same claim, without custom programming.

Interoperability testing is performed on complete field devices to improve the likelihood that the Function Block Application Process Specifications have been correctly interpreted and implemented by the product developer. The intent is that devices from different manufacturers, that have successfully undergone interoperability testing, will interoperate on the same bus segment with complete use of all specified functionality. In addition, all special or manufacturer specific features will interoperate with any conformant host system through the use of the earlier mentioned Device Description technology.

The interoperability test procedure is similar to the conformance test procedure described above in that it is performed using both automated and manual processes. The automated portion of the tests includes several hundred test cases which further test communications, but especially tests the functionality of the function block application. In addition, a very stringent physical layer test is required which is currently performed manually with standard bench test equipment. A schematic of the automated interoperability test system is given in Appendix II.

Similar to the CTK, an Interoperability Test Kit (ITK) is available from the Foundation for development purposes by device suppliers. Testing for registration is currently done only by third party testing, with the Foundation being the only authorized test agency. It is an objective to have additional test houses in other world areas qualified in the future. A self-certification program is another future objective, once sufficient experience in interoperability testing has been accumulated by the Foundation staff.

A pre-requisite of interoperability testing for registration is that the device to be tested must incorporate a communication stack that has already undergone conformance testing and has been registered conformant by the Foundation. Upon passing the interoperability test and being registered interoperable, the manufacturer will be permitted to use a distinctive certification mark on the device and in advertising. The Foundation staff maintains a catalog of all member products which are registered as interoperable. This information is also made available on its web page on the internet.

High Speed Ethernet

The currently released specification, variously called "H1" or "low speed" fieldbus, provides a solution which communicates at 31.25 kbits per second. This data rate is mandated by the physical layer specification, which is an international standard, and is not a restriction of the protocol. The data rate was selected to accommodate the requirements of process plants which tend to have complex bus topographies with long cable runs and multiple spur connections, and to support the need to use unshielded, twisted wire pair media.

A higher speed physical layer specification has always been planned for selected process applications, and for factory automation. The original "high speed" solution was to be the same protocol and function block application running on different media at optionally 1 Mbit or 2.5 Mbit per second.

In meetings between JPL and the Foundation in late 1997, JPL made an argument for adopting ethernet as a basis for the Foundation's high speed solution. JPL funded a preliminary investigation on the requirements of reading and writing fieldbus parameters over the internet.

In response to input from JPL, and because most of the Foundation board member companies recognized the merits of moving to an existing standard, the Foundation Board of Directors voted in March of 1998 to accept an alternate high speed solution based on 100 Mbit per second ethernet, also called High Speed Ethernet (HSE). A funding plan was developed and approved for the non-recurring engineering costs and a new program was launched.

This program is yet another example the intensive use of volunteers supplied by member companies to accomplish an important objective. Following the board decision, the TSC finalized the requirements and goals of the HSE Program and the Foundation staff prepared a Program Management Plan. The program was then staffed by a team of 31 full-time engineers provided by 16 member companies from Europe, Asia and the Americas. Dedicated office space was provided by one board member company, while computing and communications facilities are funded by the Foundation. The team began work in June of 1998 and is scheduled to complete the specification, including testing, by June of 1999. At that time the team will likely dissolve in its present form and be replaced by a maintenance team.

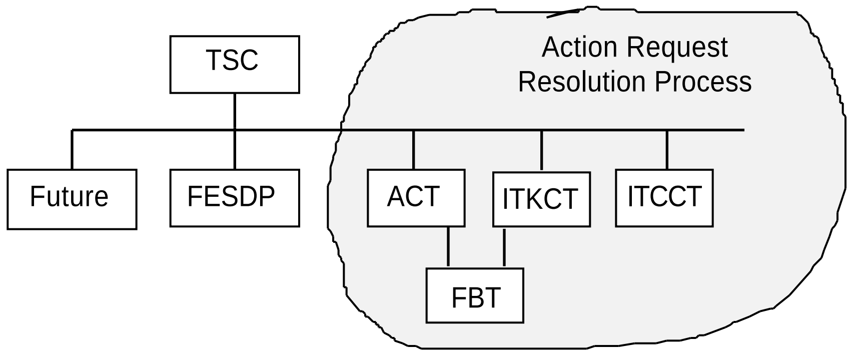
Specification projects such as the HSE Program are guided by a documented *Technical Specification Development Process,* which assures that quality procedures are used in the execution of the project. The development process requires the use of a Project Management Plan with change controls, and the use of verification and validation analysis. Specification development normally proceeds in four stages which are used to produce; alpha prototypes, beta prototypes, final prototypes, and commercial products.

Purchase orders have been issued for alpha prototypes covering approximately 75% of the specification and testing began in December of 1998. More technical details on this program will be discussed in a later section on technology.

Specification Maintenance

One of the important responsibilities of the Foundation, which is assigned to the TSC, is to assure that all specifications are maintained. Carrying out that responsibility requires a process for correcting errors, whether technical, editorial, or clerical, and to make improvements where warranted. Any member wishing to have a change made to the specifications can issue an *Action Request,* or AR. The AR is handled by a documented procedure call the *Action Request Resolution Process*.

All ARs are logged into a tracking system which assures that the current and historical status is recorded. The tracking system is administered by the Foundation staff. Referring to Figure 2, as an example of how technical teams are used, ARs related to specifications are reviewed by the Architectural Control Committee (ACT). This team currently consists of six volunteers and a Foundation staff person. This activity is part-time and meetings are held on a demand basis, often by teleconference.



KEY
TSC: Technical Steering Committee
FESDP: Fast Ethernet Specification Development Project
ACT: Architectural Control Committee
IITKT: Interoperability Test Kit Control Team
ICTKT: Conformance test Kit Control Team
FBT: Function Block Team

Figure 2. Major Technical Working Groups.

The ACT has a number of options for resolving an issue, depending on the nature of the problem. These options include use of its own expertise, referral to the Function Block Team (shown), or going to other experts inside or outside the Foundation membership. In the end, a recommendation will be made to the TSC, which will authorize the appropriate corrective action. The actual corrections may then be assigned to other teams or contracted out, as appropriate.

The TSC has technical responsibility for the two major test programs discussed earlier on conformance and interoperability. The teams responsible for these programs are the Conformance Test Kit Team (CTKT) and the Interoperability Test Kit Team (ITKT), so called because the test software and test procedures can be purchased as a kit to be used for development purposes.

If an AR is filed against either of the test programs, the same AR Resolution Process is followed, but with the AR being directed to the appropriate team. These teams consist of Foundation staff and several member volunteers. The ITKT membership includes the FBT as a sub-set. The work of both teams is generally conducted by mail and e-mail. Depending on the problem, ARs filed against either test system are occasionally the result of a problem in the specifications. In which case, the resolution is to file a specification AR and is re-cycled to the ACT.

Device Descriptions

The communications protocol and function block application in FOUNDATION™ fieldbus are both covered by comprehensive specifications. The standardization of parameters and functional behaviors is extensive. This provides a commonality which serves as the basis for multi-manufacturer interoperability.

A Device Description (DD) is a special file created for each device to define all parametric and functional extensions beyond the standard specification. The DD is written in a formal, C-like language called DDL. A standard software package called DD Services must be incorporated in every conformant host system. DD Services allows the host system to interpret all device DDs and from this, access non-standard parameters and features without custom software.

The DD technology has sometimes been compared to the printer driver used on a “host” PC. By means of the driver software, a desk computer is be able to utilize features on a new printer that were not anticipated when the PC was first put into service. The analogy is not precise, but has some qualitative value in illustrating at least the purpose the technology and perhaps suggests the potential power.

The Foundation has two major programs in support of the DD technology. One is maintenance, the other is a member/user service. Maintenance is required for DD Services and some ancillary development software, both of which are owned by the Foundation. Basically, issues that arise with the DD technology are flagged by the filing of an AR, and the same Action Request Resolution Process described above is followed, with the appropriate AR resolution team.

The member/user service program is designed to make it convenient for users of fieldbus systems to have the appropriate DDs for the devices in their systems. When a device manufacturer submits a device for interoperability testing, the associated DD must also be supplied. Part of the interoperability test is to verify that information claimed in the DD actually exists in the device. The when the Foundation registers the device as having passed the required tests, the manufacturer also has the option of registering the DD. The Foundation maintains a library of registered DDs and distributes this on CD-ROM on a quarterly basis to subscribers of the service. Internet distribution is also being evaluated as a potential future service.

Education

The demand for educational services on FOUNDATION™ fieldbus technology worldwide is significant and growing. Overview and short summary courses are needed by manufacturers and users alike for evaluating the technology and planning their organizations future direction. Manufacturers who have committed to this path need in-depth training for their development engineers. Users need training in project planning, installation and use of fieldbus products. The demand comes from all industrialized world areas.

The Foundation develops various programs to meet these needs. It is not adequately staffed to provide all training directly. Relationships have been formed with Sira Test and Certification Ltd. in England and The International Society for Measurement and Control (ISA) in the United States so that these organizations can supplement the Foundation's direct efforts. Training courses are made available in open, public seminars in the US, Europe and Asia, including China. Also, private courses are contracted by individual companies wishing to educate internal groups or departments of people quickly.

Intellectual Property

The programs discussed in the previous section are directed at: developing new specifications and software, maintaining existing specifications and software, distributing specifications and software, and providing education programs to facilitate the use of FOUNDATION™ fieldbus technology.

An effort has been made in describing the Foundation's programs to characterize the critical role played by member companies in providing volunteer services for the development of the technology that is fieldbus. An additional contribution made by the participating companies is that they must enter into a binding legal agreement with the Foundation which conveys the results of all individual and group contributions as the intellectual property of the Foundation. In addition, the Foundation has been the recipient of outright grants of critical intellectual property from member companies. The overall significance is that the Foundation has sufficient ownership of all the technology required to support the development, manufacture and distribution of FOUNDATION™ fieldbus products anywhere in the world.

The core issues are that; (a) no single company or group of companies can control the flow or use of FOUNDATION™ fieldbus technology, or in anyway limit its application and, (b) that the Foundation has the legal right to license or otherwise supply the technology to companies wishing to utilize it and, (c) the Foundation's charter assures that the technology is available for use by anyone wishing to use it.

While these conditions assure availability of the technology, they do not mean that the technology is available without certain conditions which the Foundation finds necessary to impose. Specifically, ownership of the intellectual property comes with an obligation to maintain and protect it. The financial support to meet these obligations is derived from the sale of software, licenses, and specifications; therefor these can not distributed free. In some cases, licenses may also restrict use of technology to FOUNDATION™ fieldbus applications so as to protect the FOUNDATION franchise as the world's only *interoperable* control and communication solution.

Overall, the Foundation's position on its intellectual property is that it is able to assure that companies and organizations wishing to use the technology in FOUNDATION™ fieldbus applications will be able to do so without technical or legal impediments, and that the Foundation will remain in a position to sustain the technology and it's integrity.

Standards and Specifications

International and national standards play a wide ranging role in marketing industrial products globally, though their actual importance varies by world area. Their significance is comparatively weakest in the United States, where products tend to be purchased on the basis of highest perceived value and innovation is often part of the value equation. In Europe, and particularly Germany, standards are more frequently woven into various legal statutes so that compliance with national or regional standards becomes a requirement for commerce. It is not unusual for such legislation to be enacted as a barrier to imports. Export sensitive countries such as Japan consequently are generally very supportive of strong international standards, since these tend to transcend local restrictions. In light of these realities, it is not surprising that creating an international standard is a politically ponderous process.

In August of 1984, work began on an international standard intended to become the digital replacement of the 4-20 mA analog current loop standard used throughout the process industries. The first accomplishment was invention of the term *fieldbus*. The two primary standards bodies involved in the work are the International Electrotechnical Commission (IEC) and The International Society for Measurement and Control (ISA). The committees of these two groups have met jointly since that beginning and have yet to finalize their work.

Progress in the committees was, in fact, so slow that an industrial consortium was created in 1992 to push the work through to standardization, develop and test a specification that would be a sub-set of the standard, and to support the manufacture of products to that standard. That consortium has evolved into what is today the Fieldbus Foundation, the specification which is a sub-set of the emerging standard is FOUNDATION™ fieldbus.

There is a high degree of overlap between member company engineers who have worked on both the FOUNDATION specification and the standards work within the IEC and ISA. In many cases the practical experience and testing done in FOUNDATION fieldbus has been incorporated in the proposed IEC/ISA standard to remove problems that would otherwise have gone undetected until later.

Technical work on the IEC/ISA standard is essentially done. The standard does not get approved holistically, but over time and in layers, as in the ISO Open System Interconnect layered model shown in Figure 3. At the approval level, ISA and IEC are moving at separate paces, with ISA in the lead. The current status of approval is also summarized in Figure 3.

OSI Model	Foundation	ISA	IEC
User Layer	Tested & Approved	Pub as Tech Report	Working Draft
Application Layer	Tested & Approved	Approved Standard	Approved as DIS
Data Link Layer	Tested & Approved	Approved Standard	Approved as DIS
Physical Layer	Tested & Approved	Approved Standard	Approved Standard

Figure 3. Simplified Status of Fieldbus Standards Situation.

While final approval of the standard will have commercial advantages on a worldwide basis and is highly desirable, it is not essential to the success of fieldbus. Several international controls companies have already committed to the FOUNDATION specification as corporate standards; and the end user community has responded with great enthusiasm, in part because of the promise of multi-manufacturer interoperability.

Membership

The Fieldbus Foundation is totally dependent on an active, involved membership. The associated fees provide the basic revenue stream which supports the daily operations of the organization but just as important, without an involved membership much of the work could not get done, and any work that might be done would be without purpose. It is the membership that creates the common technology, and it is the membership that puts the technology to work in useful products.

Organizations and companies can benefit from the work of the Fieldbus Foundation without becoming members. Certainly end users can buy registered fieldbus products and gain all the advantages the technology has to offer without participating directly in any of the Foundation's activities. Since the technology is open, product manufacturers can purchase the specifications, software licenses and training; and can develop products and get them registered, all without membership.

However, there are important advantages of membership for suppliers and end users alike. Over and above the fact that the Foundation would have no relevance to an industry that does not participate in the development of the technology, there are more immediate rewards.

The easiest benefit to identify for equipment suppliers is that all specifications, licenses and services are cost less for members. More importantly, participation on the technical committees gives a company a voice in the direction of the technology, and an early look at what is emerging. Both are invaluable in product planning and development. Also, the committee activity establishes a network of informed experts which becomes a resource for questions on the specifications and their interpretation.

For end users, membership offers an early understanding of the technology and how it can best be applied in their individual circumstances. It is also important for end users to have a voice in the interoperability test program, since they are directly affected by how well the principles of multi-manufacturer interoperability are realized.

The fees for membership in the Foundation are graduated based on the sales volume of the prospective member. The fee ranges from $1,500 for companies with annual sales under five million, to $15,000 for companies with sales over $100 million. For current membership details, contact the Fieldbus Foundation at (512) 794-8890, or visit their web site at www.fieldbus.org.

PART II - SYNOPSIS OF FOUNDATION FIELDBUS TECHNOLOGY

Background

The technology of FOUNDATION Fieldbus began to evolve in August of 1984 when the International Electrotechnical Commission (IEC) and The International Society for Measurement and Control (ISA)[1] met to initiate work on a new international standard. Their objectives and requirements were presented in a

[1] In 1994 the Instrument Society of America changed its name to, *The International Society for Measurement and Control*, but retained use of the abbreviation, *ISA*.

Draft Report issued three years later,[2] in September of 1987. The report presented functional guidelines which would be refined, tested and committed to a specification over the following decade.

The primary stated objective of the '87 report was, in part, "…to specify a digital, serial, communications link between primary automation devices deployed in a manufacturing/process area (the field) and higher-level automation/control devices located in a production control area (the control room)". The committees producing the draft were staffed about equally with end users and suppliers. The report dealt predominantly with physical layer issues, and [control] application requirements; the two features most obvious to end users.

Two areas of [physical] application were identified and labeled as H1 and H2. The H1 application area was intended as a digital replacement for the 4 to 20 mA analog standard in widespread use in the fluid process industries, later called *process automation*. The H2 application area was intended to extend the H1 concept to higher performance systems including high speed logic and data collection applications, later called *manufacturing automation*. The objective was one standard having the flexibility to satisfy the needs of both areas, though with different physical layers and data rates.

The H1 requirements included the need to power field devices from a single unshielded, twisted wire pair, which is also used for communication, and to be able to meet low power "intrinsically safe" standards already in use. Other major requirements included bus lengths up to 1,900 meters without repeaters, unlimited spurs, and operation in electrically noisy environments. These requirements eventually led to the comparatively low 31.25 Kbits per second communication rate.

The H2 demands accepted separate wires for power and signal, required shorter distances and accepted the cost of higher quality cabling. The data rates selected for the standard were 1 and 2-1/2 Mbits per sec.

Excerpts from the Draft Report illustrate the committee's focus, and provide an underlying understanding of the direction that FOUNDATION fieldbus was to take

Draft Report Excerpts

"3.1.4. Communication Integrity - For safe operation, the system should include error detection. A value of 20 year mean time between undetected transmission errors would assure reliable operation in the typical plant environment...." [A discussion of noise sources and RFI/EMI issues was included.]

[2] Instrument Society of America Standards and Practices 50 Functional Guidelines, Sept 9, 1987, ISA-SP50-1987-17-G

“3.1.5. Connection/Disconnection of Nodes - The bus should be capable of continued operation while a connected device (node) is being connected or disconnected…”

“3.2.6. Block Transfer - The protocol should provide a mechanism to transfer large blocks of data without delaying the communication of process data …”

“3.2.7. Redundancy - The following describes H2 applications only. The protocol should support full end to end redundancy of the fieldbus system as an option.…”

“3.2.12. Field Device Status Information - This function would add provision in the communication protocol and in the messaging capability to include a condensed indication of field device status with its current data or in the response to an output command. The condensed indication should include levels of priority.…”

“3.2.13. Addressability - It should be possible for each device or each process variable from being addressed at the user level by a unique identifier such as a tag name. For example, a human interface device could seek the location of a specific field device by a unique tag name.”

“4.5. Commissioning Data - It is important to have the correct device installed in each service during construction. The work that is currently done in loop checkout could be greatly simplified if each field device could contain the device’s tag name, serial number, range , etc. in readable , non-volatile digital memory. As soon as the device is connected to the control system, the system could then interrogate the information to confirm that communication is established with the correct device with the correct operating characteristics. The standard protocol should include provision for accessing this data.”

“4.9. Event Relative Time Stamping - The communications protocol should allow field devices to time stamp events with a resolution of at least 1 millisecond for the H1 applications of the fieldbus, [and] 0.1 milliseconds for the H2 applications of the fieldbus.…”

“4.18. Access Security - The standard should provide for access security. Multiple access levels and the ability to change the access rights should be provided.”

“4.21. Addition of Remote Control - There will be an incentive to implement a conformance class that supports functions required to implement automatic control in the transmitter, the valve positioner, or the junction box. The protocol should be able to support the required modes, the time-out gates that may be needed, the anti-windup indicators, etc.”

“4.23. Maintenance Information Capture - Some implementations of the fieldbus standard may have an incentive to include the capture of certain data associated with the field device itself. It is assumed that this function may only need the inclusion of appropriated parameter names in the highest level of the protocol. Two examples of this type of function are detailed here.” [The examples describe a maintenance record and a database to build an audit trail for all changes made to the device.]

Architectural Overview

The focus of the fieldbus committees was clearly on application requirements. What the physical layer needed to do and the environment in which it had to perform was spelled out in some detail. Also, the expectations of the control and monitoring systems were identified. Such things as the need to “hot wire” devices on an operating bus segment and the need for prioritized access privileges to device parameters on the network were plainly specified.

In addition, the customary ability in the analog world of being able to replace a device from one manufacturer with a similar device from another manufacturer, without loss of functionality or requiring special engineering, was an expectation of fieldbus. Why would a newer technology offer less capability than the older one it was displacing? Multi-manufacturer interoperability was a natural expectation. The communication scheme was actually of secondary importance, so long as it could support the requirements of the application.

Therefore, specifying a complete and well designed software application, the so-called “user layer”, became a key priority of fieldbus. In process control the prevailing model for describing a control system was (and is) the function block diagram. Because of its relative ease of use and worldwide acceptance it became the model for the fieldbus user layer; a standardized application running on top of a standardized communication stack.

Control systems require various interfaces to the physical world, as illustrated in Figure 4. Inputs consist of various measured parameters such as; pressure, temperature, switch position, shaft speed, discrete array patterns, etc. Outputs may be; shaft position or velocity, switch closure or other modulation variables generally used to control some of the inputs. In most cases some type of human/machine interface (HMI) is required at some level of the operation.

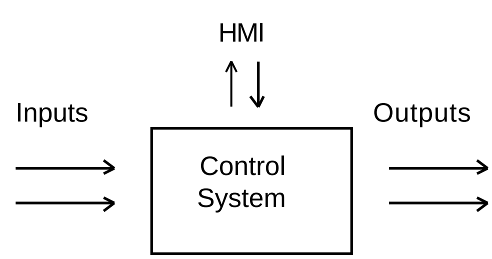


Figure 4. General Model of a Monitor and Control System.

The control system itself, as mentioned above, is modeled as an interconnected set of functions, or function blocks. Function blocks are standardized, object-oriented, software encapsulations which operate on one or more input signals to produce an output signal. In a fieldbus network function blocks reside in various the devices which are connected to the network. In configuring the network, blocks are linked in an arrangement that implements the control strategy. Blocks are distributed across the network within the devices needed to implement the control application. Thus the addition of control devices simultaneously provides the addition of network resources. All devices have a common sense of time; and the network has the ability to schedule block execution such that the requirements of input signals are synchronized with results of output signals.

Function blocks can be built into fieldbus devices as needed to achieve any desired device functionality. Devices from different manufacturers which are specified to have a particular functionality, must perform the same functions regardless of the underlying technology. Performance between manufacturers may differ, but details of the fieldbus specification assure that each device will interoperate correctly with other system components, as will be expanded on later.

For H1 fieldbus, a standard set of function blocks have been specified, tested and released. An extended set of blocks specifically for H2 applications have been specified and will be tested during the first quarter of 1999. Release of the specifications are scheduled for mid-1999. Additions to the standard blocks are possible as users of the technology define new requirements. Custom function blocks are permissible with the use of Device Descriptions and will be discussed in a later section.

While function blocks are standardized, it is recognized that the devices they reside within will have unlimited variations. Foundation fieldbus specifies the rules for an entity called a transducer block, which insulates function blocks from the physical properties of the devices in which they are used. Thus the unique characteristics of sensors, actuators and human interfaces, are interfaced with manufacturer specific transducer blocks, which in turn connect via standardized parameters to standard function blocks.

The fieldbus architecture provides a *resource block* for retaining information about each device, in the device itself. The specification mandates that the following data: manufacturer id, type of device and revision, memory size free memory space, available computational time, declaration of available features, and the state of the device, i.e., initializing, on-line, standby, failure, etc. These data must be stored in non-volatile memory. In addition, it is possible (for the user) to require that additional data such as special construction materials, calibration and repair records, and other useful information be recorded in each device. This creates a distributed data base on all components in the system.

Table 1 lists the first ten of the 29 function blocks currently specified and describes their primary functions.

Block Symbol	**Primary Functions**
AI	Analog In: Accepts digitized representation of an external analog signal from external hardware. Performs scaling, filtering, and provides high and low alarm function.
AO	Analog Out: Provides digitized representation of an analog signal to external hardware. Includes scaling, range and rate of change limits, and provides several fault-state (fail-save) options.
DI	Discrete In: Accepts 8-bit unsigned input value from external hardware. Provides filtering, optional inversion, and discrete alarms.
DO	Discrete Out: Passes 8-bit unsigned output value to external hardware. Provides optional inversion, mode shedding and fault-state (fail-safe).
PID	Proportional, Integral, Derivative Controller: Provides filtering, set point limits and rate limits, feedforward support, output limits, error alarms, and mode shedding, anti-wind-up capability, in addition to 3-term control.
PD	Proportional + Derivative Controller: Provides filtering, set point limits and rate limits, feedforward support, output limits, error alarms, and mode shedding, manual bias, in addition to 2-term control.
ML	Manual Loader: Accepts digitized representation of an analog signal from an AI block or a computer. Provides high and low output limit function and an output to other blocks. Conceptually, a controller with a human for the control algorithm.
BG	Bias/Gain Station: A simple calculation block with output limits, that connect to other blocks.
CS	Control Selector: Selects among highest, lowest or Ave. of two or three inputs (from other blocks).Provides balanceless transfer of signals.
RA	Ratio Station; Accepts signals from two AI blocks (or other source) and computes, as its output, the correct set point to be used by a controller block for the purpose of controlling a ratio of the input parameters.

Table 1. Abbreviated Description on Ten Fieldbus Function Blocks.

In addition to the primary functions indicated, there are a number of essential behaviors not easily described in a table. Examples in the following section will be used to better reveal these characteristics and their significance.

FB Application

The first example is a simple heat exchanger where steam is flowing through a coiled tube in an enclosed vessel. A process fluid is being pumped through the vessel and the objective is to heat this fluid to a precise temperature. This is illustrated in the equipment schematic in the lower half of Figure 5. In the upper half of Figure 5, a block diagram depicts the control strategy for the system.

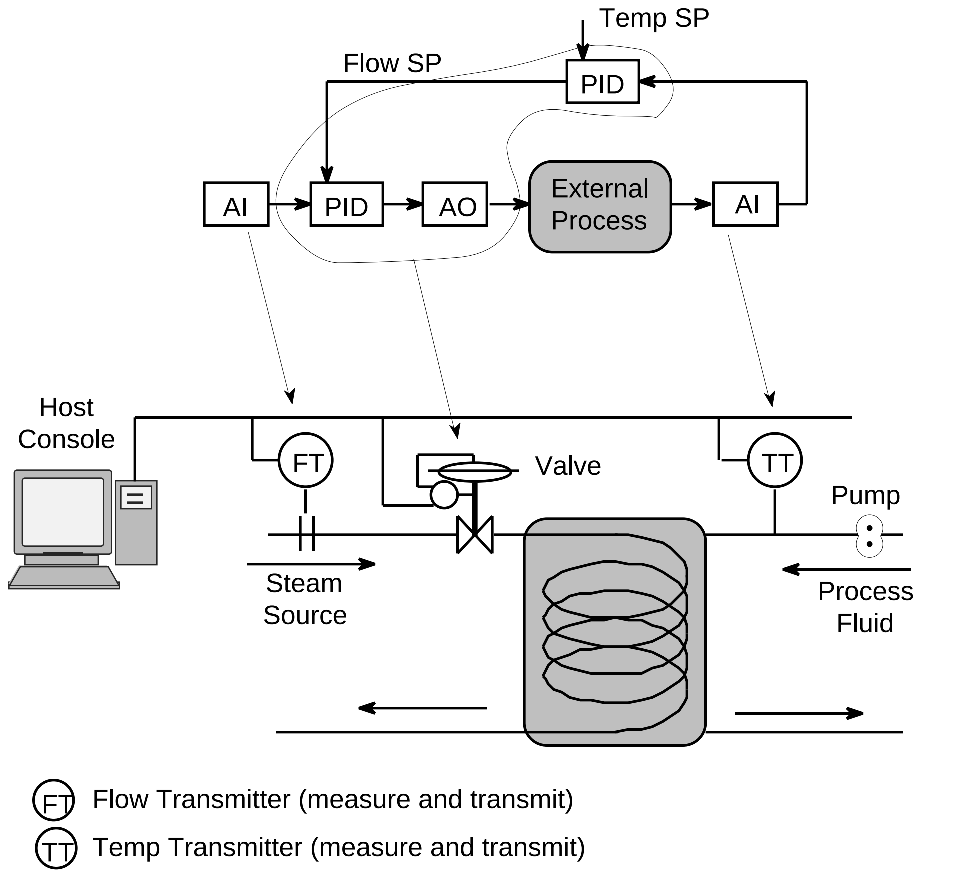


Figure 5. Illustrating Control of a Steam Heater Using Fieldbus

Looking next at the block diagram, the steam flow measurement is brought into the network by the Analog In (AI) block on the left. This value is linked to a PID block, which is the flow controller. The flow controller is receiving its Set Point (SP) from elsewhere (for now). The output of the flow PID is linked to an Analog Out (AO) block, which will manipulate an external physical variable, in this case the valve.

The valve will be manipulated as necessary to adjust steam flow to make it agree with the flow SP. Heat liberated by the steam in the tube coil will raise the temperature of the process fluid. The fluid temperature measurement is brought into the network by the AI block on the right of the diagram. This value is linked to another PID block, which is the temperature controller. The temperature PID compares the measured process temperature with the temperature SP, and computes the steam flow required to achieve or hold the process temperature at this SP. The output of the temperature PID becomes the flow SP and is linked to the flow PID.

The purpose of the flow control loop is to maintain steam flow at a specified value regardless of variations in steam pressure. The purpose of the temperature control loop is to adjust the steam loop SP as needed to maintain the specified process temperature regardless of variations in process flow or process inlet temperature.

This is a well known cascade control strategy used in process control. The equipment schematic illustrates the major hardware components of the system and also shows a Host Console on the far left. This console is where a human operator can observe the behavior of the system and make input commands such as setting the desired process temperature. This console may be several hundred feet from the process, and will normally be in an air conditioned environment. The schematic also shows the flow and temperature transmitters[3], valve, and console, all connected on a single bus. The control devices will be in the plant environment and may be exposed to severe ambient temperatures, vibration, and corrosive and/or explosive gases.

In older, centralized systems, the flow and temperature measurements are transmitted to the host where the control strategy is executed. The desired valve corrections are then transmitted back to the field. This is a FOUNDATION fieldbus installation so the control strategy shown in the block diagram will be distributed across the network; a capability unique to this technology. The functions of the AI and AO blocks must reside in the transmitters and valve, because this is where the network meets the external world.

The AI block on the left is located in the flow transmitter, the second AI block is located in the temperature transmitter. The AO block is located in the valve. All other blocks required to achieve the control strategy may be located anywhere on the network; in the host, the transmitters, the valve, or an ancillary device not shown. In this example both PID blocks will be located in the valve, we shall see why in a moment.

With FOUNDATION fieldbus all devices on a network have a common sense of time. Execution of function blocks takes place on a precise schedule so that the blocks operate in a planned sequence, and data is transmitted just in time for use. This synchronization eliminates the need for anti-aliasing filters between

[3] For those not familiar with industrial process control terminology, a transmitter is a device that includes a sensor, circuitry to operate the sensor and to compensate for all ambient influences, and a means of communicating the compensated value. Typically it is powered by the same pair of wires that are used for communication. It will likely have an explosion and corrosion proof housing.

function blocks, which would otherwise reduce bandwidth by orders of magnitude.

The communication between devices on the bus is controlled by one device on the network through a mechanism called the *Link Active Scheduler*, or *LAS*. The device which contains the LAS is called the *Link Master*. Usually this is the host device. The Fieldbus specification also defines redundant Link Masters. In an application such as the example, it would not be uncommon to include a redundant LAS in the valve. This would permit continued operation of the control system in the event that the host failed or became temporarily disconnected. During such time the only loss would be the operator's view of the process.

To more completely describe interaction between communications and function block execution, a timing diagram is presented in Figure 6. A list of the function blocks is shown on the vertical left axis. The horizontal axis is time. Execution of the function blocks is illustrated by a small rectangular icon. The thick, dotted vertical lines represent instances when scheduled data are being transmitted on the bus.

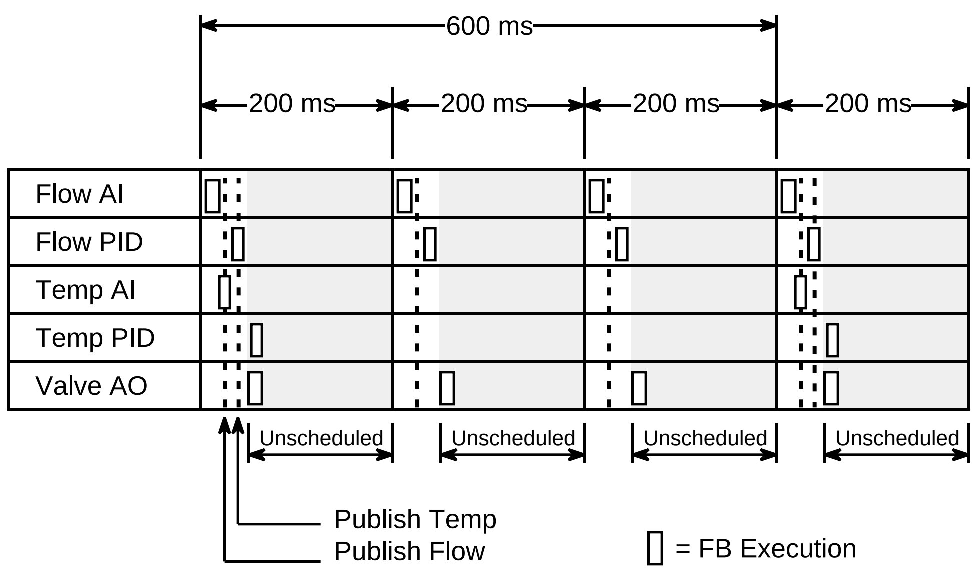


Figure 6. Example Timing Diagram for Control System of Figure 5.

To explain the sequence we will start with the execution of the AI block in the flow transmitter. The LAS has the function block execution schedule and causes the flow data to be *published* on the bus just after fresh data becomes available. Any device needing the flow data will have been configured to *subscribe* as the data appears. In this case, the host may, or may not, subscribe for various reasons. The valve will need to subscribe because the flow PID requires the information.

After the flow data publisher/subscriber sequence, the function block schedule will call for the flow PID to execute. The result of the PID calculation is passed immediately to the AO block, which is also in the valve, at which time the AO block will be scheduled to execute. Execution of the AO block will result in an update of the signal to the valve servo, outside the bus.

The entire flow control sequence is repeated every 200 milliseconds, or five times per second. (Typical process control hardware can execute this sequence as rapidly as 10 to 20 time per second, if necessary.) Each sequence requires only one transmission of data on the bus.

Execution of the temperature AI block is shown on the third row of the diagram and appears, for purposes of illustration, during the publishing of the flow data. Block execution occurs within devices and does not use any bus time, consequently there is no conflict in having scheduled the temperature block to execute at this instant. Immediately following the temperature block execution, however, the LAS will call for the temperature data to be published. As before, devices that are users of the data will have been configured to subscribe. Again in this example, it is the valve.

The temperature PID will be scheduled to execute (in the valve) and will then immediately pass its output value to the flow PID to serve as its new flow SP. Since thermal lags in the system tend to make temperature a slower changing variable, we have elected to execute the temperature sequence only every 600 milliseconds, or every 1.67 second. This is the slowest scheduled sequence on this bus segment, so this is called the *macro-cycle*. The schedules in this example are illustrative. Fieldbus function block and publisher/subscriber communications are configured to meet the dynamic requirements of the application.

The scheduled communications shown in Figure 6 occur at specific times in the macrocycle. In this example, only a few percent of the total available bus time is scheduled. In heavily loaded configurations, as much as 20 percent of the bus time may be scheduled for control communications.

The remaining, unscheduled time is indicated in Figure 6 by the shaded areas. During these intervals bus time is used for network maintenance and other non-control requirements. Examples are; operator commands (such as set point changes), checking for new or missing devices, and reporting alarms, which will be discussed in next section.

Temperature Device Failure

Earlier we mentioned that a redundant LAS could keep the system in operation in the event of a host failure. Here, we would like to consider some conditions associated with field device failures.

Suppose that the thermocouple in this transmitter failed. Ignoring the fact that this is a smart instrument and could have redundant sensors, let us assume that it does not. Obviously the transmitter can no longer publish correct process temperature values.

Every linked parameter in Fieldbus contains a value, in this case temperature, and a status. Status indicates the quality of the value, generally being Good, Uncertain, or Bad. Status also contains sub-status information giving added detail as to the general status condition.

In this example, the value picked up by the Temperature Controller will carry a status of BAD, sub-status: Sensor Failure. Local intelligence will cause the controller's mode to transition to Manual (MAN). The output will remain at its last value and will be passed to the flow controller. Normally, the steam loop could then be controlled by manual adjustments to the temperature controller. Optionally, the BAD status indication can be propagated to the Flow controller causing it's mode to go from Cascade (CAS) to Automatic (AUTO). It will then continue to hold steam flow and will become receptive to operator applied Set Point changes.

Meanwhile, the AI block in the temperature transmitter will generate an Event Notification or Block Alarm. This is a message which contains the device ID, the fact that there was a sensor failure, time-stamped to within 1/32 of a millisecond as to when the failure was detected, and other relevant information. This message will be transmitted to the host at the earliest opportunity short of interfering with the transmission of data used for control. The message will be periodically re-sent until receipt is confirmed by the appropriate authority. The same mechanism is used for process alarms and other "Events".

These actions all occur under the control of local intelligence, without the need for higher levels of intervention. The host does not poll the device for alarm information. The message preparation and control mode changes are all done locally, as defined in the Fieldbus Specification.

We have, in this example, illustrated some aspects of the power of distributed, parallel processors performing local functions and passing high level information to the central system.

Flow Device Failure

As a brief variation of the example, assume that it is the flow device that fails. In this case the flow controller will get a flow value with the status of BAD: Sensor Failure. Its mode will immediately go from CAS to Manual (MAN).

Information of this mode change is immediately passed back to the temperature controller which will then transition to the mode of I- MAN. This is a manual mode in which the controller is continually looking downstream and initializing itself to be ready for resuming control when conditions warrant.

What is new in this example is that the flow controller now does not have the information needed to control flow. It will remain in MAN and allow manual control from an operator console. The temperature controller will keep its output aligned with the flow SP as part of its initializing procedure. When the status of the flow value again becomes Good, the system will resume control without bumps or discontinuities.

As an Option, The BAD status may be propagated forward to the AO block in the valve. If this option is selected, the AO block will hold the last value for a pre-configured period of time and then initiate fault-state (similar to fail-safe). Depending on the user's selection, it will move the valve open, closed, or hold last position.

Alternative designs for this system could have employed transmitters with redundant sensors, and/or redundant transmitters, controllers and valves. All failures automatically generate and transmit a time-stamped Event Notification, as was done previously in the temperature transmitter example.

The example chosen for this discussion is relatively simple. In more complex control strategies involving; ratio controls, override with control selectors, calculation functions, feedforward, model predictive and multi-variable controls, the same principles apply.

Two key points should be made regarding the preceding discussion.

1. The behavior described is completely defined in the Fieldbus User Layer Application, which is an open specification. No other digital solution has an open, defined, User Layer specification.

2. The behavior described is mandatory and can be trusted to exist whether the devices and host are supplied by one manufacturer or four. Every Foundation registered device must support the behavior described, and must interoperate with any other registered device, and must pass an automated (interoperability) test to prove that it does.

The preceding examples do not provide a comprehensive explanation of all specified behavior, but are intended to illustrate the general level of the specifications

Maintenance Concepts

We will continue the failed transmitter example and discuss the maintenance activities that might follow. Assuming the temperature transmitter is the problem, it will be removed from the process and transferred to a maintenance area, and a replacement will be supplied from inventory.

In the maintenance shop, the problem transmitter will be connected to a test bus segment (separate from the process segment) and diagnosed. Disposition of the instrument may be;

- Return to the factory
- Dispose of instrument
- Repair device and move to inventory

In the inventory facility the device may be momentarily or continuously connected to another bus segment, separate from the process and maintenance segments.

If the three host computers associated with the process, maintenance and inventory fieldbus segments are connected on a plant “backbone” to an enterprise management computer, continuous tracking of every device in the plant is possible. Also, if maintenance is performed on the failed transmitter, that information will be stored in the device and remain with it.

The User Layer Application of every Fieldbus device contains a manufacturer ID and serial number, device type, range and operating limits, materials of construction, maintenance data, and other critical profile data.

By specification, this data must be in a format which is accessible and readable by any Fieldbus conformant interface device. The same maintenance and inventory tracking system is thus equally applicable, without custom programming, to all Fieldbus devices independent of manufacturer.

Device Descriptions

From the previous discussions it may appear that if the functionality of Fieldbus products are so tightly specified that differentiation among different manufacturer’s products could be severely restricted. It could seem that future improvements and innovations would simply be locked out because the specification did not comprehend all possible variations and future developments.

That is not an unreasonable first expectation—and it would be correct, were it not for the use of another technology exclusive to Fieldbus. In addition to the function block application, the Fieldbus User Layer Application also contains software mechanism called the Device Description, or DD.

To be Fieldbus conformant, a host system must have incorporated a software utility called *DD Services*. As described in an earlier section, this is software maintained by, and licensed from, the Fieldbus Foundation.

In addition, every registered field device must have a software file called the DD. Each device's DD is supplied to the host system. Device DD libraries are available from the Foundation on CD-ROM.

The device's DD, readable and interpreted by DD Services, contains the information necessary to allow the host to communicate with any special parameters or features that a manufacture may choose to incorporate.

As an example, valve manufacturers find it useful to accumulate the total distance a valve stem has been sliding against it's packing seal. This is a non-standard parameter and each manufacturer uses the information in its own proprietary way. However, if a manufacturer wishes to make some special parameter available to users, it is only necessary to define it in the device DD.

Suppose a supplier named the parameter *WearIndex* (WIDX). The Fieldbus protocol supports a Tag-Dot-Parameter search service, where *tag* is a device (or block) identifier. This, in conjunction with the DD technology, would allow a user to type in (for Flow Control Valve No. 423) FCV423**.**WIDX, and get a display of the value of the parameter, with engineering units, and to whatever number of decimal places the DD specifies. It is not necessary for the user to know the bus address of the device, and custom programming is not required of the host system. Other programs in the host can use the same access calls to incorporate this feature in any way that is useful.

Standard parameters, which includes all specified block parameters, are described in an object oriented file called the *object dictionary*. The DD for manufacturer specific parameters, like the example WIDX, are merely extensions of the standard object dictionary and are otherwise handled in the same way as standard parameters.

Calibration

Another illustration, and one which speaks to a more complex requirement, is device calibration. In virtually all cases the calibration procedure of an instrument or valve is unique to that design. The procedure for instrument calibration can be contained in a program and the program can be contained in the DD. This means that with no special programming of the host system, a device manufacturer's calibration procedure can be executed, including a step by step machine/human dialog, on a host interface console.

Fieldbus DD technology is open to any Foundation fieldbus product developer, but is presently not licensed for applications other than Foundation fieldbus.

Other Non-control Capabilities

By the use of DDs, it is easy to include other useful capabilities. Expanding on the wearindex example, statistics can be useful including: total run time, travel distance, number of reversals, number of starts, number of trips, etc. These can be of value in maintenance management and record keeping.

Foundation fieldbus also specifies two additional features that aid both control and non-control applications; downloading and program invocations. The downloading capability permits a manufacturer to establish a mechanism whereby devices may receive an upgrade to the field device software, remotely over the bus. This may be useful for bug fixes, version upgrades, or changes in functionality. Program invocation services permit a host to control the execution of programs within the device, again remotely over the bus. This can meet a variety of needs including on-demand diagnostics.

Several aspects of the characteristics of a Foundation fieldbus system are illustrated in Figure 7. The illustration shows a single control loop on a bus segment with two consoles. Other devices would most likely be on this segment but are not shown for simplicity. Of the equipment shown, the two consoles and the two field

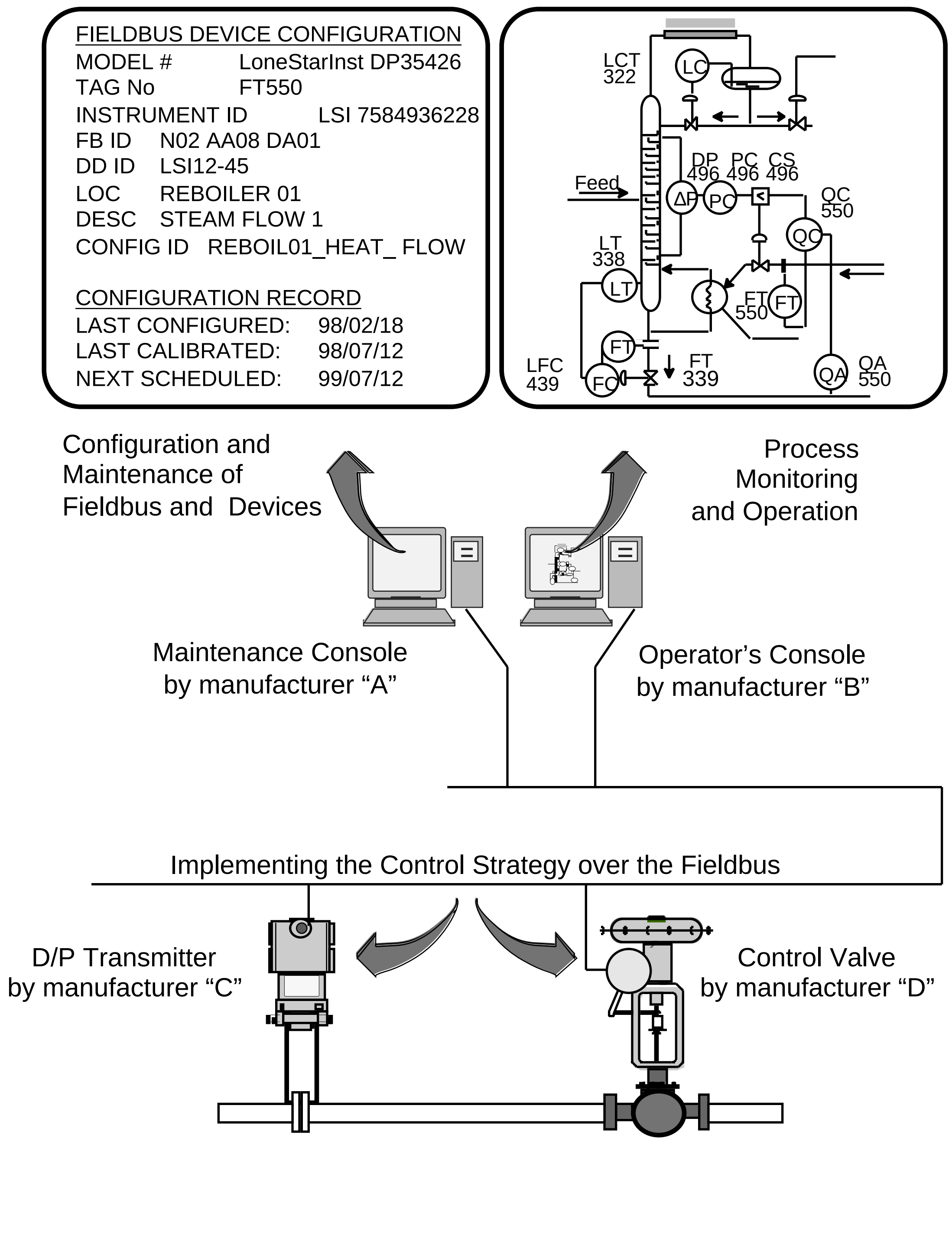


Figure 7. Illustrating Three Aspects of the Open, Interoperabile Fieldbus.

devices are each from different manufacturers. The control strategy is distributed across the network to the field devices, using function blocks specified by FF, but supplied by different vendors. Such interoperability requires;

1. A common function block application
2. Device Descriptions for manufacturer specific parameters.
3. A third party test program to assure conformance of the communications and of the application.

Only Fieldbus has a fully specified User Layer, and only Fieldbus has a comprehensive automated test system. Called the Interoperability Tester, it is used to test and certify that products conform to the Foundation User Application, and that they will interoperate with products from other manufacturers.

Communications

The function block application requires that the communications protocol provide certain services and features to support its behavior. The most fundamental features will be described here.

Communication between function blocks for control purposes was described earlier as being just in time (for function block consumption). Control is not the only communication requirement. The Link Active Scheduler (LAS) is responsible for controlling all communications. The governing mechanism is called a *delegated token*. To communicate on the bus, a device must have received a special message called a token. Tokens do not grant unlimited communication rights. Tokens delegate very specific instructions of either *what* is to be communicated, or *how long* communication may take place. In either case, the right of a device to use the network is defined and limited.

The LAS operates with three priorities. The first is to assure that communication for control occurs at precisely scheduled points in time; this was discussed in the heater example. The second priority provides for bus maintenance. This consists primarily of periodically distributing time to devices on the network for re-synchronization of device clocks, and of determining what devices are presently on the network (because devices can be dynamically added or removed). The third priority is to allow devices to communicate to each other for whatever purpose may have arisen, sending Event Notifications, for example.

The basic algorithm used by the LAS is shown in Figure 8. The logic shown is an implementation of the priorities described above. The LAS sends tokens with one of four basic instructions which are: Compel Data (CD), Time Distribution (TD), Probe Node (PN) and Pass Token (PT). When it is time for control data to be sent, the LAS will send a CD to the appropriate device and to the specific block and buffer. This instruction requires immediate publication of the data and permits no other response. This is a very short, time bounded message.

During bus maintenance, the LAS may broadcast a TD, which is concurrently subscribed by all devices. Each device, under its own local control will compare its internal clock reading with the new time value. For H1 devices, clocks will be reset to maintain accuracy within 1 millisecond. A good design feature will also cause the device to make a small hardware adjustment which improves accuracy on every reset occurrence.

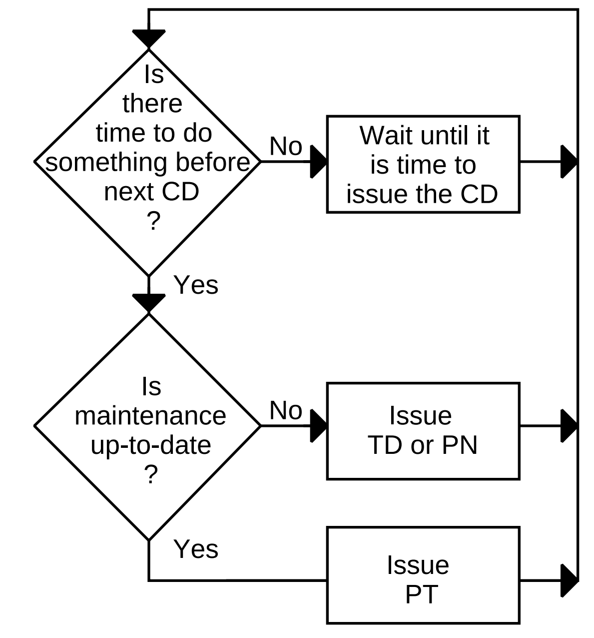


Figure 8. Algorithm for Link Active Scheduler.

The Foundation fieldbus specification provides a maximum of 256 addresses on an individual bus segment. Sixteen of these are restricted to special functions such as group addressing, and will not be considered here. Four more are for temporary devices, such as hand held maintenance tools. Another four are reserved as *default* addresses, discussed further below. This leaves 232 addresses available for field devices, but the actual number required is normally much less, and the number to be used in a given application is configurable.

When a device is configured for use on the network, it will be assigned an address which is retained in non-volatile memory (NVM). Hardwired addressing is not permitted.

The LAS maintains a list, called the *live list,* of all active devices on the network. It does this by sequentially sending a PN to every valid (configured), unused, address on the network. When a newly attached device receives a PN, it is required to return a short, defined message called a Probe Response (PR). The LAS will then initiate an identification sequence to determine the device ID, Tag number, and other information about the new device.

If the new device has not been configured with an address, it will use its own intelligence to select one of the default addresses mentioned above The LAS will probe the default addresses and proceed with the same identification sequence when a device is found. If the new device has been configured with an address that duplicates an address already in use, it will, at some point, receive a Pass Token (PT) intended for the original addressee. The new device will detect a miss-match of certain other information in the PT and will re-assign itself to a default address. This is why hard wired device addresses are not permitted.

Each device on the live list will periodically receive a PT. If the device does not return a response to the LAS, the device will be removed from the live list after three failed attempts and the LAS will issue a *Device Down* Event. While the PT is used to help maintain the live list, that is not its primary purpose.

The LAS uses the CD, TD, and PN to cause specific actions to occur under control of the LAS itself. In sending a PT to a device, it is giving the device an opportunity to communicate messages under control of the device. With the PT comes a value called the *maximum hold time.* So, although the LAS delegates control of what the device may communicate, it retains control of how long the device can use the bus. The LAS thus maintains determinism, and can assure the precise schedule required for control data.

Upon receiving the PT, a device may use as much or as little of its maximum hold time as it needs, but not more. If it has no need, it will return the PT immediately and the LAS can use the time for something else. If the device needs more time, it will return the PT at the end of the maximum hold time with a request for more time. The LAS can grant additional PTs to the device, based on a time usage calculation not discussed here.

Devices use the bus time granted by a PT to report alarms and other Event Notifications, exchange Read/Write messages with humans, communicate diagnostic information and answer requests from operators or other devices. The LAS can influence what the device communicates by providing a priority within the PT.

The communications between fieldbus devices all fall into three classifications. The method used in transmitting data for control purposes is called Publisher/Subscriber. In this model, the data to be sent is buffered, meaning the most current data will be transmitted and any older data is discarded. Data required for control must be transmitted at precise intervals and so transmission is scheduled. There is no requirement (or opportunity) for the receiver to confirm that data is correctly received. If a data point is missed, the value is immediately stale and the system will need to rely on the previous value until a future value is transmitted. Finally, the data is broadcast on the network from a single source to any device needing the data, one-to-many.

The second category was illustrated in the earlier example of a thermocouple failure where a block alarm was generated. This is called a Report Distribution and provides somewhat different features. The data to be sent is queued rather than buffered. This means that if a series of values or messages are created, none are discarded. They will each be sent in turn as time is available. It is important that such messages to be transmitted with urgency and this is best accomplished by sending them at the earliest opportunity after the occurrence of the underlying event, not on a scheduled basis. It is also important that the message is correctly received. This is assured by requiring that the appropriate recipient confirm receipt by sending a return confirmation message. Otherwise, the original transmission will be periodically re-transmitted. Reports are initiated by the sender and are transmitted as a one-to-many message similar to Publisher/Subscriber.

The third classification of communications is illustrated by an operator at a host device changing the value of a parameter in a field device, such as a set point or tuning parameter. This model is called Client/Server. The values or messages are queued, so each will be transmitted in its turn. They are transmitted in the unscheduled time during a macrocycle. Re-transmission by the sender will be repeated until a confirmation message is received from the recipient. This exchange is between one specific device and another, thus it is a one-to-one communication relationship.

The three communication relationships are summarized in Figure 9.

Communication Relationship	Publisher/Subscriber	Report Distribution	Client/Server
Characteristics	Buffered, network initiated, scheduled, unconfirmed, one-to-many.	Queued, user initiated, unscheduled, confirmed, one-to-many.	Queued, user initiated, unscheduled, confirmed, one-to-one.
Example Uses	Continuous, real-time control.	Process alarms, block alarms, trends, and other events.	Operator access such as set point and tuning changes, alarm management, access display views, remote diagnostics.

Figure 9. Characteristics and Example Uses of Communication Relationships.

<u>Data integrity</u>

All transmitted messages contain a 16-bit frame control field similar to a cyclic redundancy check. For continuous H1 communications this results in a theoretical error rate of less than one undetected error in 21 years.

H2 and High Speed Ethernet

The preceding functional description and the process plant example were qualified as being descriptive of H1 fieldbus characteristics. As explained previously, a higher speed physical layer specification has always been planned for selected process applications and for factory automation. The original high speed solution, called H2, was to consist of the identical protocol and function block application running on different media at either 1 Mbit or 2.5 Mbit per second.

In March of 1998, the Foundation Board of Directors re-directed the high speed solution and based it on 100 Mbit per second ethernet, also called High Speed Ethernet (HSE). A brief overview of the planned capabilities of the HSE technology will be presented here.

High speed ethernet, also called T-base 100, specifies a physical layer and what is called a *link layer* protocol. Without delving into protocol details, messages sent on an ethernet are described as *frames* and contain the basic information shown in Figure 10. Ethernet devices attempt to transmit all messages on an earliest opportunity basis by listening to the network and sending when it appears that no other device is transmitting. Devices are capable of detecting when message collisions occur and will re-transmit after a randomly timed delay. The data field in an ethernet frame is variable, but is limited to a specified maximum to prevent one device from holding the bus hostage.

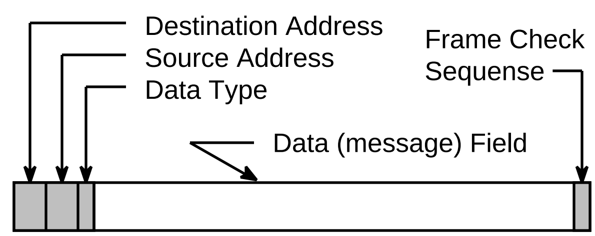


Figure 10. Data structure in an ethernet frame.

All ethernet messages are broadcast and it is the responsibility of receiving devices to filter and reject messages addressed to others. To be useful in a complex network, a much more sophisticated protocol is required. Two protocols that have gained widespread acceptance as a combination are; Transmission Control Protocol and Internet Protocol, or TCP/IP. The User Datagram Protocol (UDP) is another option in the TCP/IP suite which the HSE solution utilizes. In general, the message structure is as shown in Figure 11.

As can be seen, a fieldbus protocol data unit (PDU) is inserted in the data field of a TCP/IP packet, the packet is inserted in the data field of an ethernet frame. This solution allows the use of widely available low cost hardware, plus software compatibility with common networks used in many non-control areas of industrial plants.

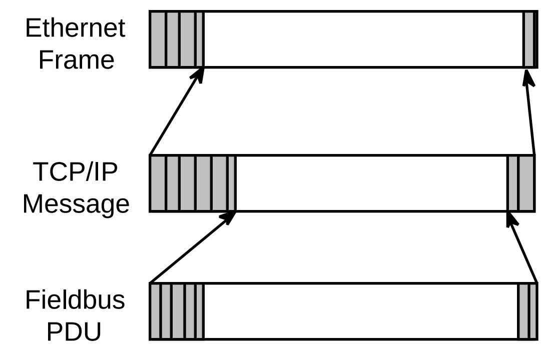


Figure 11. Nested Messages in Fieldbus HSE .

The Foundation's HSE specification addresses the requirement for redundancy; including redundant communications and HSE devices.

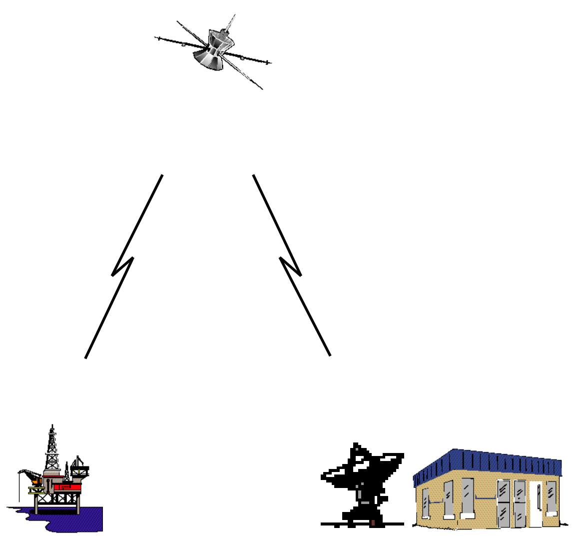


Figure 12. Off shore Oil Rig Application.

The high speed solution is being developed for use in manufacturing automation where high volumes of data must be moved at high speeds, and for process automation for use as a plant "backbone". Other applications are arising in process such as remote control of complex process units located in severe environments.

Industrial requirements such as illustrated in Figure 12 have resulted in the HSE specification being designed as a cost effective protocol for operation over satellite links for control of remote processes. The requirements are similar to those needed for control of devices and processes on orbiting spacecraft. Both applications are characterized by long transmission delays and comparatively high error rates. These lead to the need for a protocol that packs maximum data in a small packet, and a distributed control system that minimizes the communication data load.

Figure 13 summarizes the objectives of HSE fieldbus project from a functional viewpoint. The Host System is labeled Device A. Devices B and C are H1 devices and could be exemplified by the transmitters and valves of the earlier heater example. Device D is designed to communicate at HSE data rates and is called an HSE device. Such devices may require the transfer of large quantities of data, such as a gas chromatograph or a Programmable Logic Controller (PLC). Connections between HSE and H1 segments are made with a Linking Device (LD). Device E is a device based on a foreign protocol and communicates through an I/O Subsystem Interface (I/O SSI)

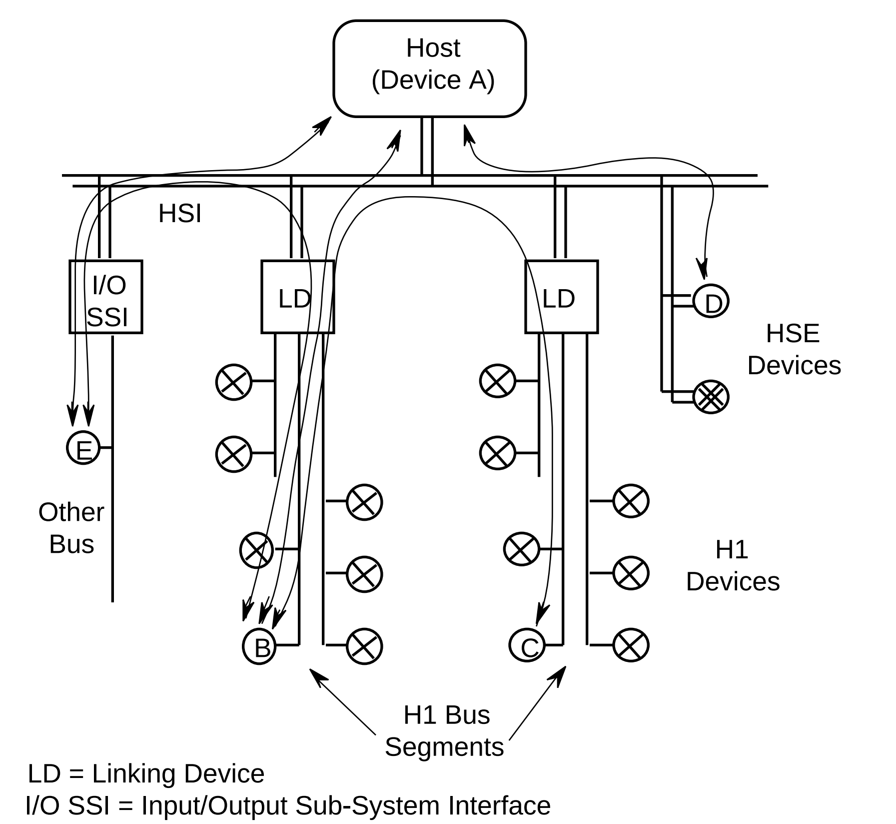


Figure 13. Logical Connections for HSE/H1 Network.

The basic interactions provided for in the fieldbus HSE solution are as follows.

A <> B   The HSE host interacts with a standard H1 device through a Linking Device. In this situation the HSE host is able to configure, diagnose, and publish and subscribe data to or from the H1 device.

A <> D   The HSE host interacts with an HSE device. In this situation the HSE host is able to configure, diagnose, and publish and subscribe data to or from the HSE device.

B <> C   In this situation, the interaction is between two H1 devices on two distinct H1 bus segments. The segments are connected to the Ethernet with Linking Devices. Communications between B and C are functionally equivalent to communications between two H1 devices on the same bus segment.

A <> E   This connection defines the relationship between a foreign device and the Foundation fieldbus application environment. Device E is a foreign device which is seen as a publisher to an HSE resident subscriber. Host Device A can treat the data stream from the I/O Subsystem Interface in the same manner as it treats the data stream from Devices B, C and D.

E <> B   This is a situation where a foreign device wishes to subscribe to an H1 resident device or vice versa. The foreign device may be another network, a device connected via telecommunications services, or a directly connected end-system.

Linking Devices (LD) accept and deliver Foundation fieldbus PDUs to and from an H1 bus segment. They add or remove the TCP/IP encoding needed for a frame to be sent on or received from the HSE segment. They also provide a routing service so that messages transmitted over the HSE from one LD to another, will be accepted by the correct LD. The Input/Output Sub-System Interface (I/ O SSI) is similar to a LD but must also provide proper mapping of foreign data into and out of fieldbus function blocks.

The Foundation HSE network can be configured in either a bus topology as shown in Figure 14, or as a switched network as shown in Figure 15.

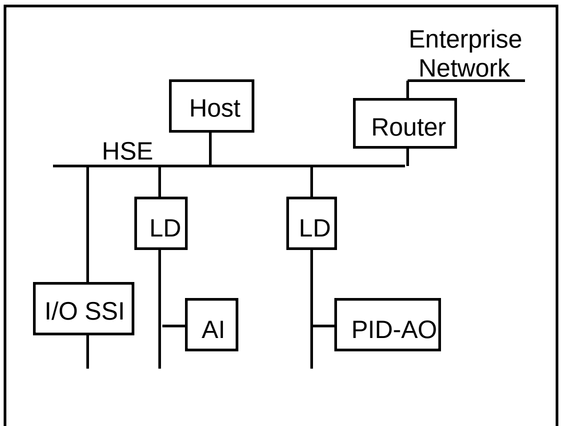


Figure 14. Ethernet Bus Configuration.

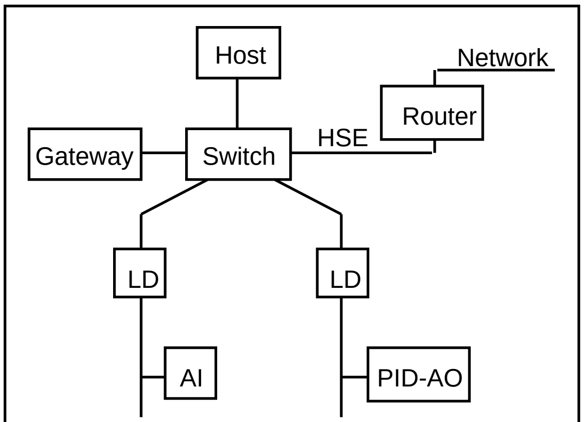


Figure 15. Switched Ethernet Configuration.

Summary

The specifications that ultimately emerged from the efforts of the fieldbus committees and industrial consortia are owned and maintained by the Fieldbus Foundation and are promoted as Foundation fieldbus.

The solution distributes functionality across the network and makes maximum use of intelligence in the individual field devices. It provides a deterministic protocol for real-time control. It defines a standardized, object-oriented, function block model for application software and a unique Device Description technology to achieve multi-manufacturer device and host interoperability without custom programming.

PART III – STEPS FOR TECHNOLOGY TRANSFER

Introduction

Foundation fieldbus technology represents a modern, de-centralized communication protocol with an integrated monitoring and control application based on an object oriented function block model. The technology is consistent with the SuperMOCA objectives and offers significant cost savings by virtue of its architecture, its technology, and standardization aspects. The fundamental infrastructure for government/industry cooperation already exists, but needs development.

Applicability of Technology

It has been emphasized that Foundation fieldbus is a specification for both communication and control. The communication aspect has a priority scheme designed in. Data required for real time control has the highest priority and communication of this data is deterministic. Data required for maintaining the health of the network has the next priority and is communicated on an acyclic, first opportunity first basis. Other communications at lower priorities are similarly acyclic and first opportunity transmissions. Communications are secure, and confirmation is required where appropriate, as described earlier.

The control aspect is based on a function block model which uses standardized, encapsulated functions which are combined in various ways to implement any required control strategy. A majority of real world signals are either continuous analog values, or discontinuous discrete values. Thus four basic function blocks (Analog In, Analog Out, Discrete In, and Discrete Out) serve to transfer a majority of information into or out of the network. This is true, independent of the nature of the devices required in the system. The earlier part summarizing the technology illustrated[4] the use of AI blocks for importing temperature and flow data, and an AO block to provide a control signal to a valve. This was a realistic representation of a simple industrial application.

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[4] See Figure 5

An application of Foundation fieldbus technology to Space Mission Operation and Control was implemented and tested in the 1997-1998 time frame by the Jet Propulsion Laboratory (JPL). In this example, a two axis motorized Cannon camera and a Lowrance GPS Receiver were interfaced to a custom designed NASA Search and Control Block (NASA-SCB). In the actual test system, GPS signals were not integrated into the SCB, but were visible at the Host. The demonstration system is illustrated in Figure 16.

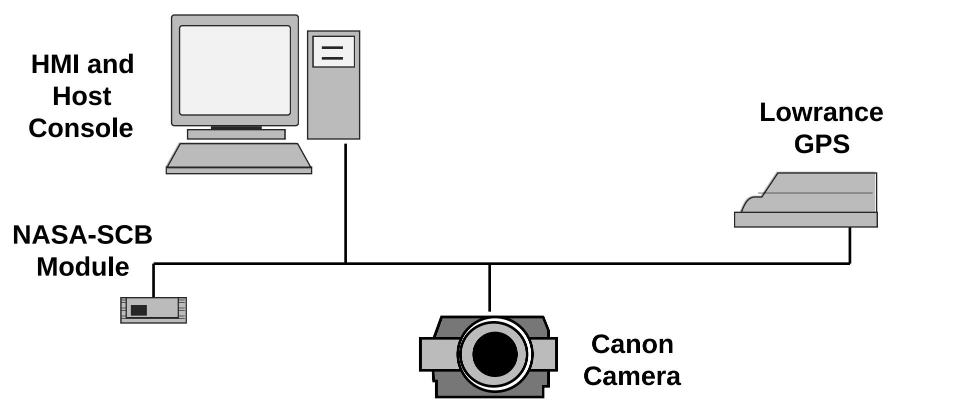


Figure 16. Demonstration network for space application.

The function block configuration for the system is shown in Figure 16. The oval objects represent the devices shown in Figure 17. The function blocks in each device are shown, as are the linkages between function blocks. The host device, shown in the upper right hand corner of Figure 17 provides a user interface where high level commands are entered. The two-headed arrow to the search control block (SCB) in the control module indicates two-way communications with between these points.

The SCB is a custom block which implements the algorithms needed to translate high level commands, e.g., the search volume and pattern for a mosaic of images. The algorithms in the SCB should also have access to the longitude and latitude data from the GPS.

Looking at the oval which represents the camera, there is a block labeled *Transducer Camera* at the bottom of the oval. Fieldbus uses software objects called *transducer blocks* to provide an interface between the fully specified and standardized function blocks, and the unique technology of various physical devices.

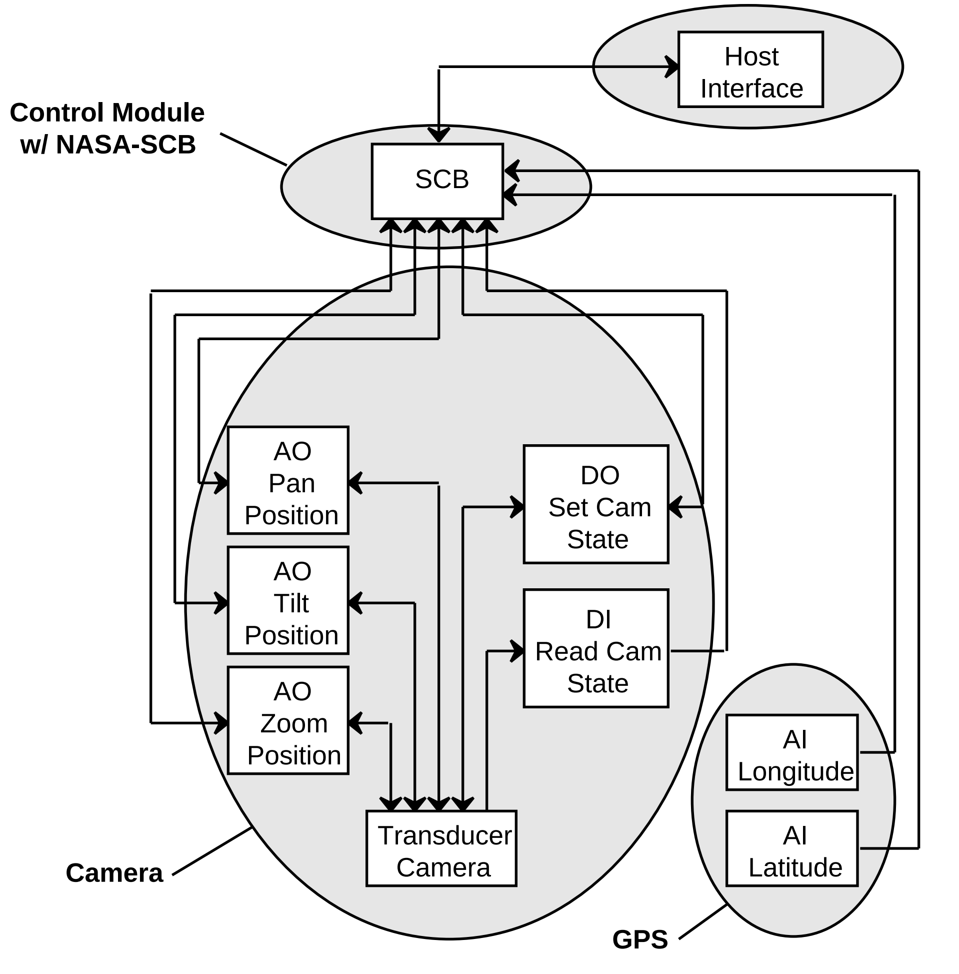


Figure 17. Function block configuration for demonstration network.

To explain the camera operation, envision some high level command from the console being interpreted in the SCB. Assume this results in an instruction to change the camera zoom from 14% to 23% of full scale (or 2.8X to 4.6X). This signal is sent to the AO zoom block. There is a “back-calculation” signal from the AO block to the SCB which allows search control to know that the AO is working, and to provide the information needed to properly handle limit conditions when they occur. The AO zoom block passes the zoom data to the transducer camera block, which translates the instruction into the format required by this particular camera. The actual camera zoom state is return by a *read back* signal to the AO zoom block. Again this is to assure that the operation is correct and to properly handle limits.

If a failure were to occur in the camera where, for example the zoom motor froze, the status of the read back signal would indicate bad, motor failure. Just as in the process control example described earlier, the AO zoom block would revert to manual mode, or at some point proceed to a fail safe state, this information would be relayed back to the SCB, which would force its control action to a manual mode. The AO zoom block would issue a time-stamped block alarm containing the critical information about the device and the failure. The alarm will be periodically re-broadcast until acknowledge by the properly configured authority, most likely the host console.

If, in this illustration, the camera were to be sourced from an different vendor, Acme Camera for example, the exact same control strategy and behavior could be assured. What would be required of Acme Camera, is that it contain a Transducer Camera block which provides the translation between Acme's unique pan, tilt and zoom controls, and the standard fieldbus AO function blocks. From that point forward the strategy, modes of control, scaling, alarming, and operator interface are identical. If Acme Camera offered useful, unique features, these would be incorporated through the camera's Device Description so, just as in the process automation example, innovation is enabled not discouraged.

In this, and the process control application presented earlier, the examples have been kept simple in order to more easily convey the concepts. It is no doubt obvious to the reader that additional kinds of input and output , control, and other function blocks would be required for a broad range of applications. Indeed, a reasonable list of advanced function blocks have been specified[5] and, at this writing, many have been implemented and tested. Perhaps more importantly, the rules for object oriented function block design have been defined and specified. Thus future needs can be met by the creation of special blocks such as the NASA SCB in Figure 17. If widespread need is recognized for a special block, the organizational infrastructure is in place to promote the block to become part of the specification.

While the examples cited have been simple, the requirements of a wide range of industrial control problems were used in the development of the fieldbus function block application specification. These included control of industrial and utility boilers, paper making machines, refineries, distillation columns, discrete parts assembly lines, high speed bottling plants and so forth.

While control problems in space applications involve different environments and different time scales than industrial applications, control problems in every sphere of application have much in common. The problems of controlling the attitude of a spacecraft or pointing a tracking station antenna are surprisingly similar to the problems in the control of complex industrial applications. Control of an exothermic chemical reactor, cross-coordinated controls of a modern power generating station, load distribution and safety interlocks of a power grid, or forward modeling control of catalytic cracking tower are all examples of

[5] See Table 1.

complex control strategies which are routinely implemented using a function block model.

The tested, proven, open Foundation fieldbus specification is well suited to the requirements of monitoring and controlling remote space systems. The incorporation of high speed ethernet (HSE) and the TCP/IP protocols with H1 fieldbus, discussed in the technology part, provides a technology well suited to detailed, local monitoring and control, yet capable of interfacing to the communications between spacecraft, operations center, and ground terminals.

Cost Savings Due to Technology and Architecture

Significant cost savings are inherent in the underlying fieldbus architecture. These savings derive from multi-vendor interoperability, distributed control and resources, and local intelligence supporting a distributed data base.

Multi-vendor interoperability attacks costs on several fronts. First of all it makes competition feasible. There are many components in a monitoring and control system that can be supplied by competitive vendors; valves, sensors, cameras, servos, gyros, etc. If these devices must conform to the Foundation fieldbus specification, and pass an extensive interoperability test to prove it, then the user is no longer locked in to specific suppliers because of proprietary protocols.

Interoperability reduces costs by eliminating the requirements for bridges, gateways, and custom programming to get system components integrated. In addition, tools for configuration and testing become standardized and can be used on multiple products. This standardization increases product unit volumes of common tools, which further reduces cost and provides an opportunity for improved quality and reliability. These common tools and the widespread use of a standard technology, improves the knowledge base of the engineers and technicians working on the systems, and reduces the cost of training.

Because Foundation fieldbus is becoming the international standard for process and manufacturing automation, many components required for industrial applications will be implemented and field tested over the next few years. These implementations will provide a base of experience from which a new generation of space devices can benefit.

Decentralizing control and distributing system functionality has a number of interesting effects. To a significant degree, it automatically scales the computing resources in the system to the requirements of the system. For example, when some number of measurement points are added to a system, the resources for scaling, alarming and calibrating those points reside in the added devices. The addition of a primary control element such as a valve or servo, means that the control function, limits, alarms, interlocks and so forth are automatically included. In a very real sense, *the network is the control system.* Scaling the network up or down, scales the resource in proportion. The cost associated with major revamping central facilities is largely mitigated.

With decentralized control, raw data is not sent to a central computer for processing, the data reduction is done locally, and high level information is communicated. This means that the host system need not scale in direct proportion to the nodes on the network. It also reduces control-related network traffic by approximately half. The improved bandwidth can generally be used in either improved performance, or reduced cost by fewer segments.

The additional safety and reliability of autonomous control loops should also be recognized. A network made up of numerous H1 bus segments integrated into one or more redundant HSE links is extremely robust. The H1 segments themselves can be configured with redundant measurements, redundant controls, or completely redundant control loops. If a segment is isolated from the network by some failure, it can be designed with the ability to run autonomously. These are proven capabilities, inherent in the technology, not add-on structures.

The fieldbus architecture provides a *resource block* for retaining information about each device, in the device itself. The specification mandates that the following data: manufacturer id, type of device and revision, memory size free memory space, available computational time, declaration of available features, and the state of the device, i.e., initializing, on-line, standby, failure, etc. These data must be stored in non-volatile memory. In addition, it is possible (for the user) to require that additional data such as special construction materials, calibration and repair records, and other useful information be recorded in each device. This creates a distributed data base on all components in the system.

A host device can collect information on all active system components to maintain a current record of the structure. By keeping spare components in a fieldbus monitored inventory, the architecture of fieldbus supports both inventory control and tracability of system changes. These functions can be automated, rather than performed by costly and error susceptible manual record maintenance.

Cost Savings Due to Cooperation Among Suppliers, Integrators and End Users

A standard such as Foundation fieldbus can only be achieved through the cooperative efforts of multiple suppliers, and it can only be adapted to a new application area by the cooperation of all parties. Obviously, developing a single standard with the work being shared by several participants should be less costly than each participant independently developing a proprietary specification.

The savings are not only in the development or adaptation of a standard, open solution, but through the benefits of multi-vendor interoperability. System integrators can benefit from a plug-and-play philosophy, rather than creating custom software to interface the many components of a system.

End users should expect to benefit from the lower costs placed on suppliers and integrators, but also from their own progress on a learning curve associated with an open standard. The overall shared experience among users, integrators and suppliers builds competence, standard solutions evolve, and the process of continually re-inventing functionally equivalent wheels is terminated.

Organization for Government and Industry Cooperation

The general philosophy of this Technology Transfer Plan is to work within the existing Fieldbus Foundation infrastructure, using processes and procedures already in place. There are seven steps to this Plan.

1. The Fieldbus Advocate
2. Membership drive
3. Critical committee and team memberships
4. Training
5. Specification extensions
6. Technical program and budget
7. Funding model

These steps are essentially what has taken place in each of two earlier stages in the evolution of the fieldbus specification. The first stage was dominated by suppliers of process automation equipment (PA Application Area) and resulted in completion and testing of the H1/H2 specification. The second stage was dominated by suppliers of manufacturing automation equipment (MA Application Area) and represents the work currently in progress on the HSE program. What is envisioned by this plan is a third stage that basically replicates the activities of stages 1 and 2 by addressing aerospace applications, or an AS Application Area.

<u>1 The Fieldbus Advocate (Customer)</u>

Many manufacturers in the process and manufacturing sectors have long been able to offer products based on proprietary protocols that offer numerous advantages due to the use of digital technology. However, no single manufacturer can supply all the products needed for the complete automation of a refinery, a paper mill, or an automobile assembly line. So, the mixing of products from multiple manufacturers was required, but expensive; and interfaces could often degrade performance. In addition, users want the ability to purchase from a variety of suppliers based on their own individual preferences, be that price, performance, or service.

As described in Part I, manufacturers of industrial control equipment have more recently worked together in a cooperative effort to satisfy the demands of their customers for an open, interoperable, communications and control standard. These manufacturers did not join together in a cooperative effort because they preferred to abandon their proprietary solutions, but rather because of pressure from their customers. Furthermore, suppliers having a narrow product range were forced to interface with several proprietary protocols; an inefficient and costly practice for them.

The narrow product range suppliers tended to side with users in advocating an open, interoperable solution. In contrast, the broad range suppliers, having more of an interest in perpetuating their own proprietary protocol, had different motives for participating in the standards efforts. However, as a viable solution became visible, interest from users intensified, and it became necessary for all major participants to cooperate.

The critical point is that suppliers who are able to provide a proprietary protocol, will not relinquish that position voluntarily. As long as it is acceptable to their customers, any supplier will find it advantageous to maintain exclusive control of the technology used, and force others to bear the cost of interfaces.

For an open, interoperable standard to be adopted, the direction must be forced by the customer. Narrow product range suppliers may be willing cooperate, or even take a leadership role in promoting an open standard, but the *essential factor is the customer*.

Emergence of Foundation fieldbus was painfully slow because the customer base is tremendously fragmented. It is fragmented by geography, type of manufacture, and competition among end users, and by dis-information spread by opponents to an open standard. Therefore, pressure from the customer base was not consistent nor coordinated, and required leadership from the narrow product range suppliers for its ultimate success.

It would seem that the aerospace customer has an advantageous position with respect to providing supplier direction; ultimately the customer is the government. Perhaps this naively ignores the fact that the government is represented by an array of agencies capable of specifying and purchasing communications and control equipment. How to achieve coordination of buying practices among these agencies is not within the scope of this plan. However, to make technology transfer successful, the driving force must come from a consequential customer. A major entity such as JPL must commit to the use of Foundation fieldbus and make it mandatory for a significant mission. Whether JPL is in fact the correct agency is not within our purview, so we will refer to this entity the *Fieldbus Advocate.*

2 Membership drive

As described in Part I, manufacturers of industrial control equipment have worked together in a cooperative effort to satisfy the demands of their customers, the end users. The independent, not-for-profit, Fieldbus Foundation provides an infrastructure for such cooperation and a repository for shared technology, but the productive work of creating and testing an open specification is performed by volunteered engineers from member companies.

It will be necessary for the aerospace industry to participate in a number of committee positions in the Fieldbus Foundation. Membership in the foundation is an eligibility requirement for these positions. Once the Fieldbus Advocate is committed and an program is identified, it will be essential for participating supplier companies to be made aware of the foundation and their obligation to participate.

The Foundation presently has approximately 125 member companies world wide. It would be reasonable to expect 25 to 30 aerospace companies to be represented in the Foundation. The Advocate should inform the Foundation of candidate companies and the Foundation will mount a campaign to educate and recruit.

While the basic work for Foundation fieldbus has been done, refinements and extensions are expected to be required for it to be useful in space applications. Three such areas have been identified[6]. These are (1) the requirement for space qualified communication components, (2) a higher bandwidth physical layer, and (3) potentially additional, as yet undefined, function blocks.

Item (2) is currently being addressed by the HSE program. Items (1) and (3) are issues to be addressed in the future by a technical committee representing the aerospace industry, discussed in step 4, below.

3 Critical committee and team memberships

The Foundation charter calls for an eleven member board of directors. All seats are currently filled, but there are typically one or two changes during a year. Board members are elected by the membership for a period of two years, five or six being elected in alternate years. If a board member resigns in mid-term, the remaining board has the power to appoint a replacement.

[6] J.K. Jones, E.L. Klaseen, and L. Neitzel, *Cost Reduction Through Application of Fieldbus Technology to Space Mission Operation and Control*, ISA Aerospace Industries Division/Test Measurement Division 44th International Instrumentation Symposium, May 6, 1997, Reno, NV.

This has traditionally been someone from the departing member's company, but it need not be.

Assuming that the membership targets of 25 to 30 companies are achieved, it would be appropriated for aerospace companies to fill two board positions. This might take more than a year to accomplish, but an interim solution for board representation could be negotiated, until openings become available.

In addition to board membership, aerospace company members should make at least two volunteer engineers available for membership on the Technical Steering Committee (TSC), and one to participate on the Architectural Control Team[7] (ACT). Among other responsibilities, the TSC is the final arbiter of specification changes and aerospace must have strong representation.

There should be one or two members on the Executive Committee (Xcom). This group serves as an advisory group to the president of the Foundation and is sometimes used for special assignments. Foundation management will need advise and assistance from the new industry segment.

In addition to these positions, it will be necessary to create a Specification Analysis Task Force (SATF) to review the existing specifications and identify any extensions and enhancements that may be needed to satisfy the requirements of space mission applications. This group should be reasonably small for the sake of efficiency, but large enough to represent all application areas. Our tentative recommendation is this should be between five and seven members. Members of this task force should be prepared to make a full-time commitment for a period of one to two months. The deliverable from the SATF is a set of requirements, not a solution. These requirements will require review by the TSC to confirm that that they can not be met with the existing specification.

Upon approval of the requirements document, a Specification Design Task Force (SDTF) should be organized to actually develop specifications to satisfy the new requirements. This should include at least some members from the SATF. The size and duration of this task force will depend on how extensive the additional requirements are. The size and schedule of the specification development team for the HSE program is described in Part I, as an example.

Finally, the Foundation will need to identify and recruit an individual from the aerospace industry to serve on the Foundation staff in support of the AS Application Area. The recommended positions are summarized below, the consultant entry is discussed in several of the following paragraphs.

[7] See Figure 2.

Position	Staffing	Estimated Commitment
Board Member	Two	4-8 days/yr, each
Xcom	One or two	18-24 days/yr, each
TSC	Two minimum	18-36 days/yr, each
ACT	One	18-24 days/yr
Marketing Committee	Optional	18-24 days/yr, each
SATF	Five to seven	28-56 days/yr, total for each
SDTF	To be determined	To be determined
FF Staff member	One	Full time
Consultants	Three to six	To be determined

4 Training

The Fieldbus Foundation conducts training programs several times per year. These include: Fieldbus Overview (1 day), Advanced Technical Workshop (2 days) and Device Description Workshop (3 days). It is recommended that everyone serving on committees and task forces, other than board members, enroll in all of these courses.

It is also recommended that team members contract consultants early on for custom workshops targeted at how devices are implemented and how to create and use special function blocks. It is proposed that this should be done in at least two stages. First, before any changes are proposed, so as to help identify the envelope of the current specification. Then, again later, to help define test implementations.

5 Specification extensions

Identifying the application requirements and defining the limitations of the present specification are the initial functions of the SATF. The first step is to clearly define the communication requirements. These requirements are then evaluated against the present specification to identify any extensions that may be required. It is recommended that a small cadre of consultants be hired to assist with analysis of the existing specification. Some help will be available from the Foundations but experts with implementation experience will be needed for a full understanding of the protocol and the function block application.

6 Technical program and budget

Following the merger that resulted in the former ISP Foundation becoming the Fieldbus Foundation, the TSC went through Step 5 above. It then developed an estimate for the non-recurring engineering (NRE) costs to complete of the H1/H2 specification, and identified the probable staffing requirements. The board voted a funding plan in which each board member company made an interest free, no-recourse loan of $250,000. This funding was used for contract development of the conformance test system, the interoperability test system, consultants, prototype hardware and similar expenses. In addition, the board member companies provided the majority of the volunteer manpower applied to developing the specifications.

This entire technical planning process was repeated for the HSE program and another budget was developed for the NRE costs required to execute it. In this case, a total of 19 interested member companies made $50,000 loans to fund the program, and provided extensive volunteer engineers. In return these companies will have products well in advance of non-participating companies.

In cooperation with the TSC, the SATF should take the output of their work from Step 5 and develop a technical program which will satisfy space mission requirements. This program must include staffing requirements, which will become the SDTF. There will certainly be NRE costs in the form of prototype construction, new test cases for the test systems, and consultants for selected expertise. There will also be a need for a group of full time volunteered engineers to write and test the specification.

While this program and budget can really only be developed after Step 5 is completed, a preliminary budget will most likely be needed before that time. It is suggested that the HSE program would be a reasonable model. An example organization of the required teams and how they would fit in the Foundation infrastructure is shown in Figure 18.

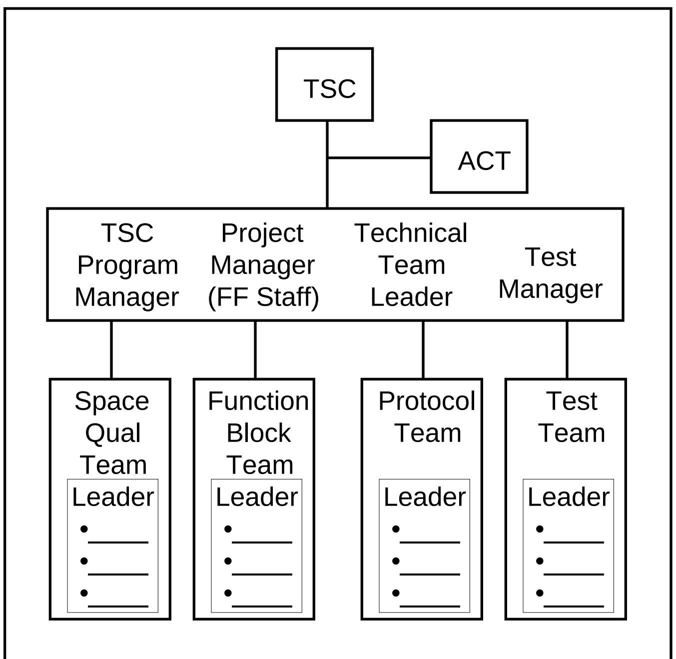


Figure 18. Prototype Organization for the SDTF.

The large block of four participants reporting to the TSC represents the management team for a set of anticipated SDTF programs. The TSC Program Manager is the primary liaison between this group and the TSC. The FF Staff person would be the full time engineer on staff at the foundation. This person would be responsible for all administrative duties, at a minimum. The Technical Team Leader is the top technical manager for all technical development. The Test Manager is in charge of test program design and execution.

The four teams shown are responsible for space qualified communications, new function blocks, protocol additions, and test programs. This is an appropriate and typical structure, though not the only possible organization. The team functions shown are likely possibilities, but the actual assignments will be defined by the work of the SATF.

7 Determine funding model

It is recommended that the Fieldbus Advocate be prepared to fund the appropriate companies for the volunteer help, and to fund the NRE cost. An estimate of these costs is not available at this time.

Summary Of Benefits and Transfer Requirements

Foundation fieldbus represents an extensive combination of technology and organizational infrastructure. It provides a tested, open specification for interoperable devices which are designed support diagnostics, monitoring and control in mission critical applications. But the technology goes well beyond written specifications. It includes multiple sources for development and configuration tools, communication stacks and applications software. There are automated test systems and documented test procedures for testing stack conformance and device interoperability

There is an established infrastructure which supports the test programs, maintenance and improvements in the specification, maintains and supplies key software utilities, and provides an organization where companies (industrial and government suppliers alike) can cooperate on technology development and exchange.

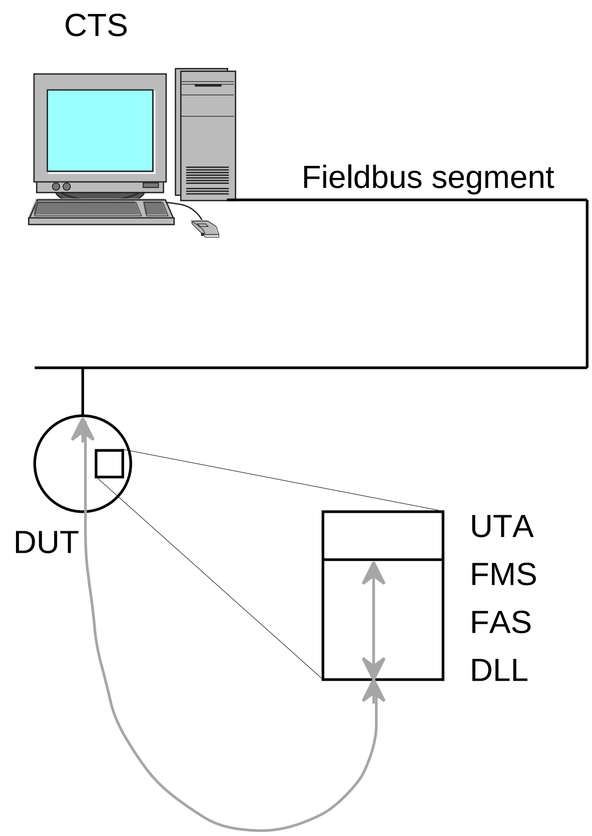
Industrial process and manufacturing automation, and space mission applications share many common requirements. Both can benefit from devices having multi-manufacturer interoperability, both need realtime scheduled and unscheduled bus access, they must deal with physical resource constraints, and both need increasing device autonomy. There is a common need for monitoring and control systems where subsystems can report error and health conditions, and perform remote calibration, diagnostics and program execution.

There is a shared need for a standardized communication interface to the physical resources of a device that does not in turn require that the physical resources themselves be standardized. Similarly, there is a shared need for a standardized, modular application that accommodates the addition of unforeseen functionality, without the need for special tools and custom programming.

By meeting all of the above requirements, Foundation fieldbus offers to both industrial and space mission requirements the potential for dramatic reductions in cost. As has been shown, these savings arise from the technology and the architecture of fieldbus itself, and from the cooperation among suppliers, system integrator and end users.

APPENDIX I
SCHEMATIC OF THE CONFORMANCE TEST SYSTEM

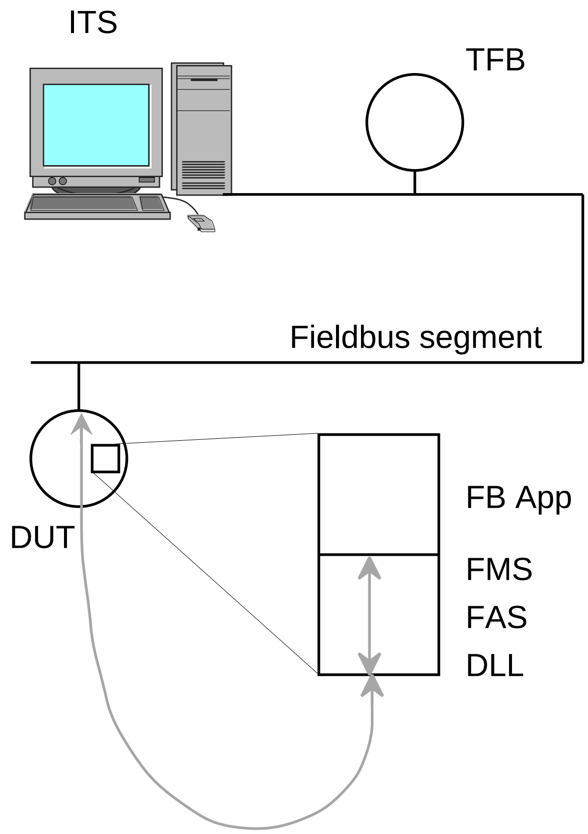
The automated conformance tester is used for testing communication stacks against the Foundation specification. It requires that an upper tester agent be integrated to interface of the application layer, which is FMS. The test is then conducted by the execution of several hundred test cases which cause communication between the tester and the agent. A report is generated identifying test cases passed and failed.



DUT: Device Under Test
UTA: Upper Tester Agent
FMS: Fieldbus Messaging System
FAS: Fieldbus Access Sublayer
DLL: Data Link Layer
CTS: Conformance Test System

Schematic of Conformance Test System.

APPENDIX II
SCHEMATIC OF THE INTEROPERABILITY TEST SYSTEM



DUT: Device Under Test
TFB: Test Function Block
FB App: Function Block Application
FMS: Fieldbus Messaging System
FAS: Fieldbus Access Sublayer
DLL: Data Link Layer
ITS: Interoperability Test System

Schematic of Interoperability Test System.

The automated interoperability tester is used for testing the function block application, in a specific device design, against the Foundation specification. It requires the DUT use an already tested communication stack. The tester includes a TFB with the test system software and a fieldbus device that contains a special test function block. Linkages are set up between the DUT and the TFB and several hundred tests are executed to assure the device and application will interoperate properly with other tested devices.